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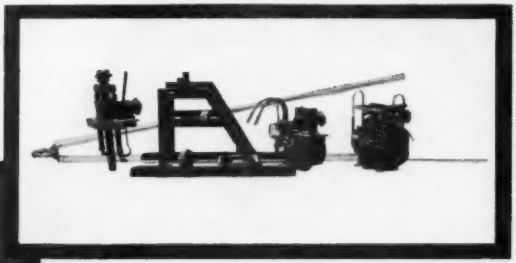

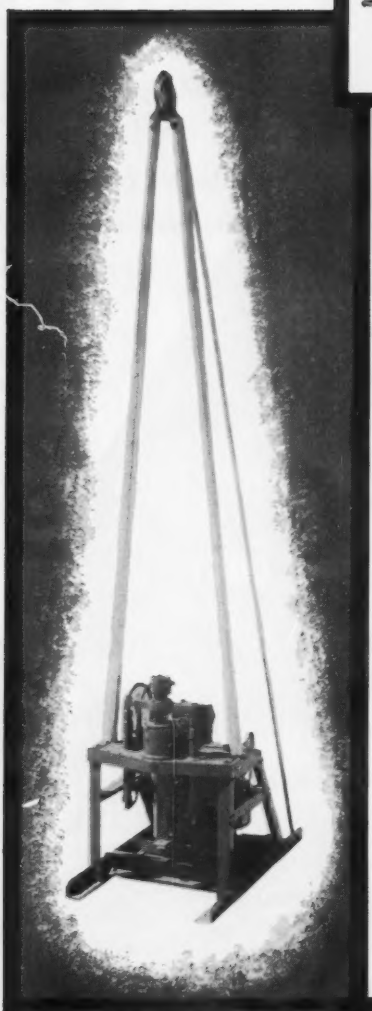

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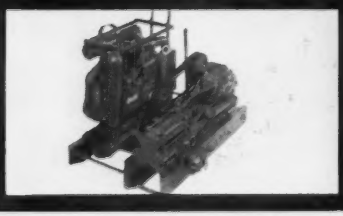

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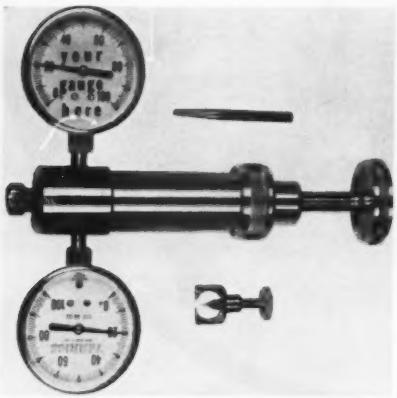

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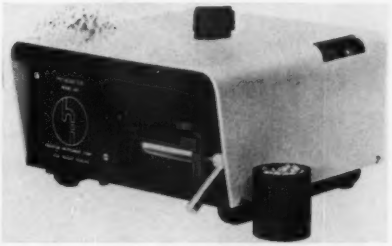

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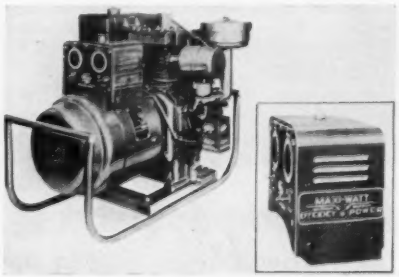

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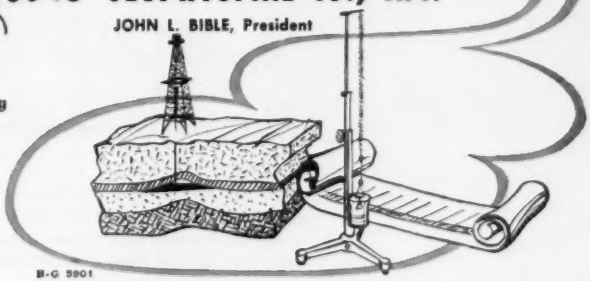

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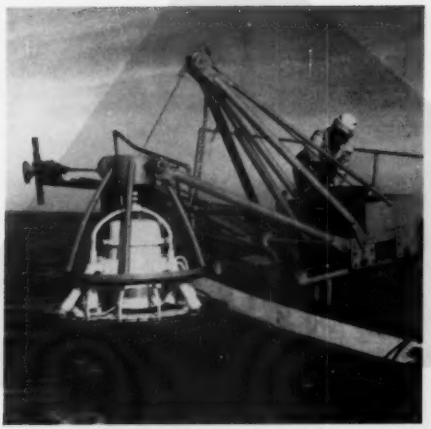

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VOLUME XXV JUNE, 1960 NUMBER 3

GEOPHYSICS

A COMPREHENSIVE SYSTEM OF AUTOMATIC COMPUTATION IN MAGNETIC AND GRAVITY INTERPRETATION*

ROLAND G. HENDERSON†

ABSTRACT

In the interpretation of magnetic and gravity anomalies, downward continuation of fields and calculation of first and second vertical derivatives of fields have been recognized as effective means for bringing into focus the latent diagnostic features of the data. A comprehensive system has been devised for the calculation of any or all of these derived fields on modern electronic digital computing equipment. The integral for analytic continuation above the plane is used with a Lagrange extrapolation polynomial to derive a general determinantal expression from which the field at depth and the various derivatives on the surface and at depth can be obtained. It is shown that the general formula includes as special cases some of the formulas appearing in the literature. The process involves a "once for all depths" summing of grid values on a system of concentric circles about each point followed by application of the appropriate one or more of the 19 sets of coefficients derived for the purpose. Theoretical and observed multilevel data are used to illustrate the processes and to discuss the errors. The coefficients can be used for less extensive computations on a desk calculator.

INTRODUCTION

An investigation was undertaken for the purpose of using the U. S. Geological Survey's stored program electronic digital computer in magnetic and gravity interpretations. The fundamental problem was considered to be the downward continuation of potential fields. This is related to the problem of upward continuation and both have strong "overtones" in derivative calculations. The limitations and inadequacies of the various proposed methods of calculation, much discussed in the literature [e.g. Nettleton (1954), Trejo (1954), Dean (1958)], were confirmed by tests on an abundance of well-controlled theoretical and practical field data accumulated by the Survey. It was advisable, therefore, to reexamine this area of calculation with a view to improving formulas and techniques. In the course of the study, a rather comprehensive formula was derived from which most of the important quantities currently in use can be obtained. Moreover, the formula has been used to obtain mutually consistent sets of coefficients which, when incorporated into computer programs, yield values of high accuracy in a minimum of machine time.

* Paper read at the 28th Annual Meeting of the Society at San Antonio October 15, 1958. Manuscript received by the Editor January 12, 1960. Publication authorized by the Director, U. S. Geological Survey.

† U. S. Geological Survey, Washington, D. C.

Programs of the various computations discussed in this paper have been written for Burroughs computers and are available from the Computation Branch of the U. S. Geological Survey, Washington, D. C.

Except for the various sets of coefficients, which by their nature are non-unique, nothing essentially new is claimed in this report. The theory and relative merits of the derived fields in question have been adequately treated in the work of Evjen (1936), Tsuboi and Fuchida (1938), Hughes (1942), Bullard and Cooper (1948), Peters (1949), Henderson and Zietz (1949a and b), Elkins (1951), Baranov (1953), and others. Since they all stem from potential theory, there is little difference in principle among the various methods. There is, however, considerable difference in the results depending upon how the details of the numerical analysis have been carried out. Baranov (1953) has given more attention to this aspect than most writers.

BASIC FORMULA

In this paper practical results have been emphasized somewhat at the expense of mathematical elegance. Our approach is quite unsophisticated. Let $\Delta\Phi(x, y, 0)$ be any observed component of a magnetic or gravity anomaly field represented on a map by iso-intensity contour lines. Conventionally, we lay down a square grid of mesh interval, say a, and interpolate the values of $\Delta\Phi(x, y, 0)$ at each mesh point. The origin of the right-handed system of co-ordinates is taken at the point where a field is to be computed, with the z-axis positive vertically downward [see Figure 1]. $\Delta\Phi(x, y, z)$ satisfies $\nabla^2[\Delta\Phi(x, y, z)]=0$ and accordingly may be treated by the methods of potential theory as far as the nearest singular point.

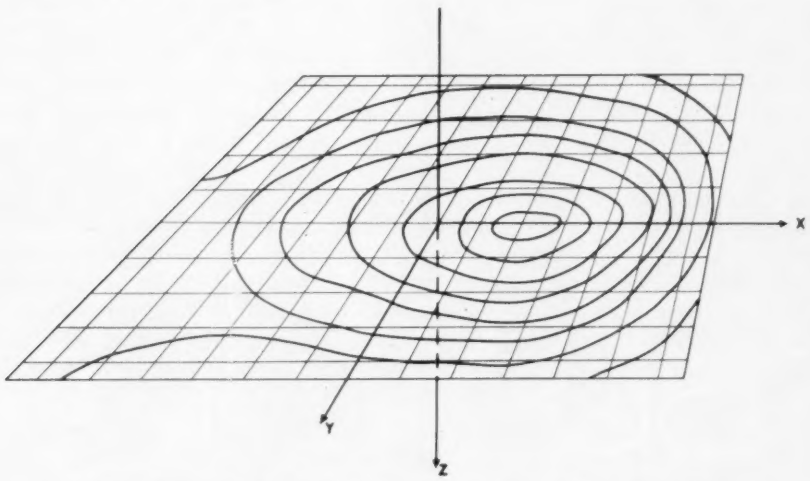

FIG. 1. Representation of field $\Delta\Phi$ $(x, y, 0)$ on the plane of observations; grid and co-ordinate system.

Briefly stated, the problem is to compute $\Delta\Phi(x, y, z)$ below the plane of observations ($z=0$) and $\partial(\Delta\Phi)/\partial z$ and $\partial^2(\Delta\Phi)/\partial z^2$ on and below that plane from the interpolated $\Delta\Phi(x, y, 0)$ values as input on modern electronic digital computing equipment.

The familiar integral solving the Dirichlet problem for a plane (the so-called upward continuation integral) is used to compute $\Delta\Phi(z)$ at n points an interval a apart along the vertical line $x=y=0$ above the plane. The integral in polar co-ordinates is,

$$\Delta\Phi(-ma) = \int_0^\infty \frac{ma\Delta\bar{\Phi}(r)rdr}{(r^2 + m^2a^2)^{3/2}}, \qquad (1)$$

$$m = 1, 2, \cdots, n,$$

and where

$$\Delta\bar{\Phi}(r) = \frac{1}{2\pi}\int_0^{2\pi} \Delta\Phi(r, \theta)d\theta, \qquad (2)$$

the average value of $\Delta\Phi$ on circles of radius r about the point. Experimentally we found that radii $r=0$, a, $a\sqrt{2}$, $a\sqrt{5}$, $a\sqrt{8}$, $a\sqrt{13}$, $a5$, $a\sqrt{50}$, $a\sqrt{136}$, $a\sqrt{274}$, and $a25$ adequately sample the field. The number of mesh points falling on the circles having these radii is respectively 1, 4, 4, 8, 4, 8, 12, 12, 8, 8, 12. Next, a Lagrange interpolation polynomial is fitted to $\Delta\Phi(0)$ and the n values $\Delta\Phi(-ma)$ computed from (1) to obtain the approximation formula,

$$\Delta\Phi(z) \approx \sum_{m=0}^{n} \frac{(-1)^m z(z + a)(z + 2a) \cdots (z + na)}{a^n(z + ma)(n - m)!m!}\Delta\Phi(-ma). \qquad (3)$$

This formula is certainly valid above the plane. Proceeding in a heuristic manner we investigate the possibilities of using (3) as an extrapolation formula for computing $\Delta\Phi(z)$ below the plane. The values of the parameters n and a are unspecified. By applying the formula to a variety of theoretical and experimental data for which $\Delta\Phi(-ma)$ and $\Delta\Phi(z)$ were known we determined useful practical values for n and a. Satisfactory results were obtained with $n=5$, but for $n>5$ the polynomial coefficients become inordinately large in relation to the data they operate upon. The mesh interval, a, depends upon the data, i.e., the spacing of observed points, lateral extent of anomalies, "sharpness" of anomalies, etc. If a is too small, oscillations laterally are likely to develop; if a is too large, the coverage will be inadequate. A mesh interval equal to about one fourth the depth to the top of the disturbing body as determined by common depth rules [see Vacquier, et al (1951), Nettleton (1940)] is usually satisfactory.

UPWARD CONTINUATION COEFFICIENTS

The accuracy of formula (3) obviously depends upon the accuracy of $\Delta\Phi(-ma)$ as computed from the upward continuation integral (1). A careful numerical

evaluation employing a mean value theorem over each interval $r_i \leqq r \leqq r_{i+1}$ was carried out. The integral (1) is replaced by the sum

$$\Delta\Phi(-ma) \approx \sum_{i=0}^{N-1} [(r_{i+1} - r_i)^{-1} \int_{r_i}^{r_{i+1}} \Delta\bar{\Phi}(r)dr]ma \cdot \{[r_i^2 + (ma)^2]^{-1/2} - [r_{i+1}^2 + (ma)^2]^{-1/2}\} + 0\left(\frac{1}{r_N}\right). \quad (4)$$

The last term in (4) involves the unavoidable truncation error which for r_N sufficiently large is only of academic interest and involves an error which some authors arbitrarily force into the last coefficient to make the set sum to unity. The details of the evaluation of (4) will not be given here. Suffice it to say that the success of the process depends upon the manner in which the quantity in the first bracket of (4), viz.,

$$(r_{i+1} - r_i)^{-1} \int_{r_i}^{r_{i+1}} \Delta\bar{\Phi}(r)dr,$$

is evaluated. The criterion used for its proper evaluation was that the resulting $\Delta\Phi(-ma)$ when used in (3) should yield a $\Delta\Phi(z)$ having the correct functional behavior with changes in depth. For example, off the axis, the gravity anomaly of a sphere increases with depth, reaching a maximum at $z_{max} = z_c - [(x^2+y^2)/2]^{1/2}$, where z_c is the depth to the center of the sphere. For depths greater than z_{max} the anomaly decreases monotonically. For the point whose co-ordinates are (10, 5) in Table I, this character of $\Delta\Phi(z)$ along a vertical line is clearly shown in the lower half of the left column, for a sphere whose center is at (0, 0, 10). By expressing $\Delta\Phi(r)$ in terms of polynomials of the second degree we allow for its non-linear variation over most intervals $r_i \leqq r \leqq r_{i+1}$ and achieve the desired behavior of

TABLE I

COMPUTED UPWARD AND DOWNWARD VALUES COMPARED WITH EXACT VALUES. GRAVITY ANOMALY OF SPHERE, CENTER AT (0, 0, 10)

z	Coords, (0, 0)		Coords, (5, 0)		Coords, (10, 5)	
	Exact values	Computed values	Exact values	Computed values	Exact values	Computed values
−5	55.56	55.83	47.44	47.56	28.64	29.26
−4	63.78	63.87	53.27	53.30	30.43	30.94
−3	73.96	73.91	60.14	60.10	32.24	32.63
−2	86.81	86.65	68.27	68.19	34.00	34.27
−1	103.31	103.15	77.94	77.86	35.64	35.78
0	125.00	125.00	89.44	89.44	37.04	37.04
1	154.32	154.59	103.08	103.26	38.05	37.88
2	195.31	195.32	119.10	119.71	38.49	38.10
3	255.10	251.81	137.46	139.13	38.12	37.44
4	347.22	330.18	157.42	161.92	36.71	35.57
5	500.00	438.21	176.78	188.41	34.02	32.09

TABLE II

UPWARD CONTINUATION COEFFICIENTS

i	$\Delta\bar{\Phi}(r_i)$	$K(r_i, 1)$	$K(r_i, 2)$	$K(r_i, 3)$	$K(r_i, 4)$	$K(r_i, 5)$
0	$\Delta\bar{\Phi}(0)$	0.11193	0.04034	0.01961	0.01141	0.00742
1	$\Delta\bar{\Phi}(1)$	0.32193	0.12988	0.06592	0.03908	0.02566
2	$\Delta\bar{\Phi}(\sqrt{2})$	0.06062	0.07588	0.05260	0.03566	0.02509
3	$\Delta\bar{\Phi}\sqrt{5})$	0.15206	0.14559	0.10563	0.07450	0.05377
4	$\Delta\bar{\Phi}(\sqrt{8})$	0.05335	0.07651	0.07146	0.05841	0.04611
5	$\Delta\bar{\Phi}(\sqrt{13})$	0.06586	0.09902	0.10226	0.09173	0.07784
6	$\Delta\bar{\Phi}(\sqrt{25})$	0.06650	0.11100	0.12921	0.12915	0.11986
7	$\Delta\bar{\Phi}(\sqrt{50})$	0.05635	0.10351	0.13635	0.15474	0.16159
8	$\Delta\bar{\Phi}(\sqrt{136})$	0.03855	0.07379	0.10322	0.12565	0.14106
9	$\Delta\bar{\Phi}(\sqrt{274})$	0.02273	0.04464	0.06500	0.08323	0.09897
10	$\Delta\bar{\Phi}(\sqrt{625})$	0.03015	0.05998	0.08917	0.11744	0.14458

$$\Delta\Phi(-m) \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) K(r_i, m)$$

$\Delta\Phi(z)$ with depth as shown in the right column of Table I for the point (10, 5). By putting a = unity and successively evaluating (4) for $m = 1, 2, \cdots, 5$, we obtain the five sets of coefficients adopted for upward continuation given in Table II. Symbolically, we write the working formula,

$$\Delta\Phi(-m) \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) K(r_i, m), \tag{5}$$

where $K(r_i, m)$ is the set of coefficients which operate on the center value and the ten ring-average values $\Delta\bar{\Phi}(r_i)$ in the computation of $\Delta\Phi$ at m grid units above the plane. In the upper half of Table I, values for a sphere computed from (5) are compared with theoretical values for the points whose co-ordinates are indicated.

With $\Delta\Phi(-ma)$ thus determined and, a, properly chosen, formula (3) becomes a comprehensive formula in the sense that most derived fields of interest can be obtained from it; moreover, it includes as special cases certain formulas appearing in the literature.

DOWNWARD CONTINUATION COEFFICIENTS

If in formula (3) we put $z = a$ we get the essential formula of D. S. Hughes (1942) for the nth approximation of an anomaly at one mesh interval below the plane. Successively putting $z = 2a$, $3a$, $4a$, $5a$, we obtain formulas for computing downwards to these levels—all using the same ten ring-averages $\Delta\bar{\Phi}(r_i)$. After some algebraic manipulation involving substitution of (5) in (3), we have the working downward continuation formula which we write as

$$\Delta\Phi(k) \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) D(r_i, k), \tag{6}$$

TABLE III
DOWNWARD CONTINUATION COEFFICIENTS

i	$\Delta\bar{\Phi}(r_i)$	$D(r_i, 1)$	$D(r_i, 2)$	$D(r_i, 3)$	$D(r_i, 4)$	$D(r_i, 5)$
0	$\Delta\bar{\Phi}(0)$	4.8948	16.1087	41.7731	92.5362	183.2600
1	$\Delta\bar{\Phi}(1)$	−3.0113	−13.2209	−38.2716	−89.7403	−183.9380
2	$\Delta\bar{\Phi}(\sqrt{2})$	0.0081	0.4027	1.7883	5.1388	11.8804
3	$\Delta\bar{\Phi}(\sqrt{5})$	−0.5604	− 1.9459	− 4.7820	− 9.9452	− 18.6049
4	$\Delta\bar{\Phi}(\sqrt{8})$	−0.0376	0.0644	0.5367	1.7478	4.2324
5	$\Delta\bar{\Phi}(\sqrt{13})$	−0.0689	− 0.0596	0.1798	0.8908	2.4237
6	$\Delta\bar{\Phi}(\sqrt{25})$	−0.0605	− 0.0522	0.1342	0.6656	1.7777
7	$\Delta\bar{\Phi}(\sqrt{50})$	−0.0534	− 0.0828	− 0.0560	0.0718	0.3606
8	$\Delta\bar{\Phi}(\sqrt{136})$	−0.0380	− 0.0703	− 0.0900	− 0.0890	− 0.0571
9	$\Delta\bar{\Phi}(\sqrt{274})$	−0.0227	− 0.0443	− 0.0639	− 0.0802	− 0.0921
10	$\Delta\bar{\Phi}(\sqrt{625})$	−0.0302	− 0.0600	− 0.0891	− 0.1173	− 0.1444

$$\Delta\Phi(k) \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) D(r_i, k)$$

where $D(r_i, k)$ is the set of coefficients for computing $\Delta\Phi$, k mesh intervals below the plane. The five sets of coefficients are given in Table III.

The calculation is carried out in two steps. First, one goes over the "gridded" anomaly getting the average values on the ten circles about each grid point. Next, the center point value and its associated ring-average values are each in turn multiplied by the appropriate coefficient of the set $D(r_i, k)$ and the products are summed. A peculiar advantage of this system is that once the ten ring-averages have been obtained, they may be used repeatedly for field computations at different depths or for the derivative computations to be discussed below.

The coefficients in Table III, when tested on a variety of theoretical and practical multilevel data, consistently give highly satisfactory results. Some idea of the accuracy to be expected can be gleaned from Figure 2 where the coefficients have been used to compute a central profile of the composite gravity anomaly of two spheres; depth of centers, ten units; separation of centers, ten units. True values are indicated by solid lines; computed values by dots. This figure also demonstrates the well-known resolving power of downward continuation. Note that at $z=0$, it is not at all apparent that there are two bodies.

Figure 3 shows the true and continued vertical magnetic profiles over a vertically magnetized square plate $0.5\times10\times10$ units buried 5 units below the datum plane. In addition to demonstrating the accuracy of the continuation process, this illustration has interesting implications with respect to the depth method of Vacquier, et al (1951). This method assumes that anomalies originate from prisms whose depth extent is, mathematically at any rate, infinitely large. Some attempt was made by Vacquier et al to show that satisfactory results were obtained as long as the depth extent-to-depth ratio was not less than unity. If we apply this method to the anomaly of Figure 3 at $z=0$, we fail to

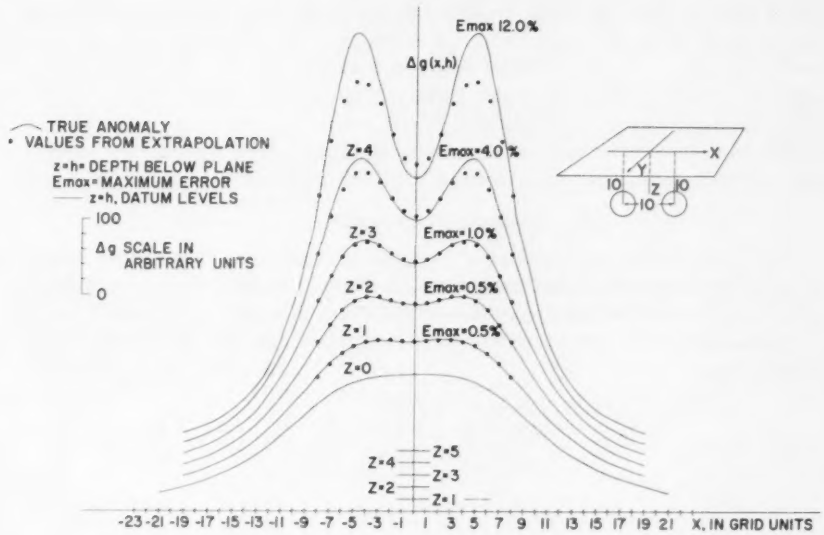

FIG. 2. Downward continuation of composite gravity anomaly of two spheres.

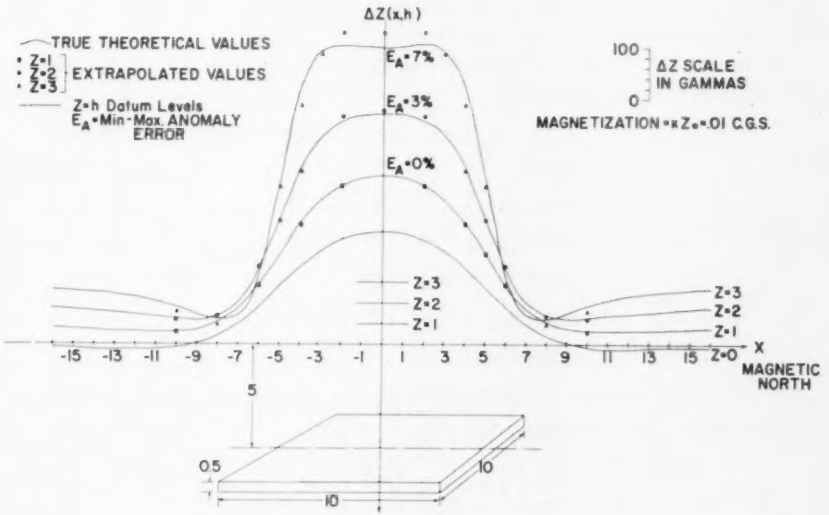

FIG. 3. Downward continuation of vertical intensity anomaly of vertically magnetized square plate.

get a good estimate of depth because the depth extent-to-depth of burial ratio is too small. If on the other hand, the anomaly is first continued to a depth of $z=3$ (so that the depth of burial becomes 2 units) and then the depth method applied, a good estimate of depth (total 4.5 units) is obtained despite the fact that the depth extent-to-depth ratio is still somewhat less than unity. The implication is that downward continuation can bring within the purview of existing methods anomalies that otherwise might be incorrectly analyzed for depth.

DERIVATIVE FORMULAS

The comprehensive character of the general expression (3) is further demonstrated by the fact that derivative formulas can be obtained from it by differentiation. In its present form the differentiation is somewhat complicated. It can be more readily carried out when (3) is written in the following equivalent determinantal form,

$$\Delta\Phi(z) \approx -\,|\,V\,|^{-1}\begin{vmatrix} 0 & 1 & -z/a & (z/a)^2 & \cdots & (-z/a)^n \\ \Delta\Phi(0) & 1 & 0 & 0 & \cdots & 0 \\ \Delta\Phi(-a) & 1 & 1 & 1 & \cdots & 1 \\ \Delta\Phi(-2a) & 1 & 2 & 2 & \cdots & 2^n \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \Delta\Phi(-na) & 1 & n & n^2 & \cdots & n^n \end{vmatrix}, \tag{3a}$$

where $|\,V\,|$ is the Vandermonde determinant obtained by deleting the first two rows and columns of (3a) [see, e.g., Householder (1953)].

Putting $n=5$ in (3a) and differentiating once with respect to z we have a first vertical derivative formula

$$\frac{\partial(\Delta\Phi)}{\partial z} \approx -\,(a\,|\,V\,|)^{-1}\begin{vmatrix} 0 & 0 & -1 & 2(z/a) & -3(z/a)^2 & 4(z/a)^3 & -5(z/a)^4 \\ \Delta\Phi(0) & 1 & 0 & 0 & 0 & 0 & 0 \\ \Delta\Phi(-a) & 1 & 1 & 1 & 1 & 1 & 1 \\ \Delta\Phi(-2a) & 1 & 2 & 2^2 & 2^3 & 2^4 & 2^5 \\ \Delta\Phi(-3a) & 1 & 3 & 3^2 & 3^3 & 3^4 & 3^5 \\ \Delta\Phi(-4a) & 1 & 4 & 4^2 & 4^3 & 4^4 & 4^5 \\ \Delta\Phi(-5a) & 1 & 5 & 5^2 & 5^3 & 5^4 & 5^5 \end{vmatrix}. \tag{7}$$

If in (7) we put $z=0$, we have a formula for calculating first vertical derivatives on the plane of observations which may be written,

$$\left[\frac{\partial(\Delta\Phi)}{\partial z}\right]_{z=0} \approx \frac{1}{a}\left(1+\frac{1}{2}+\frac{1}{3}+\frac{1}{4}+\frac{1}{5}\right)\Delta\Phi(0) + \frac{1}{a}\sum_{m=1}^{5}\frac{(-1)^m 5!}{m^2(m-1)!(5-m)!}\Delta\Phi(-ma).$$

The last formula and Bickley's 6-point formula as given by Southwell (1946) are identical. Successively putting $z=a$, $2a$, etc. in (7), we obtain first derivative formulas at depth.

To obtain sets of coefficients for computing $\left[\partial(\Delta\Phi)/\partial z\right]_{z=k}$ using the ten ring-averages $\Delta\bar{\Phi}(r_i)$ we take $a=$ unity, put (5) into (7) and after some algebraic manipulation obtain the working formula

$$\left[\frac{\partial(\Delta\Phi)}{\partial z}\right]_{z=k} \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i)\, D'(r_i,\, k),$$

where $D'(r_i,\, k)$ are the first vertical derivative coefficients appropriate for k mesh intervals below the plane. The coefficients are given in Table IV.

In a similar manner we differentiate (7) with respect to z and obtain a second vertical derivative formula,

$$\frac{\partial^2(\Delta\Phi)}{\partial z^2} \approx -\,(a^2\,|\,V\,|)^{-1} \begin{vmatrix} 0 & 0\ 0\ 2 & -6(z/a) & 12(z/a)^2 & -20(z/a)^3 \\ \Delta\Phi(0) & 1\ 0\ 0 & 0 & 0 & 0 \\ \Delta\Phi(-a) & 1\ 1\ 1 & 1 & 1 & 1 \\ \Delta\Phi(-2a) & 1\ 2\ 2^2 & 2^3 & 2^4 & 2^5 \\ \Delta\Phi(-3a) & 1\ 3\ 3^2 & 3^3 & 3^4 & 3^5 \\ \Delta\Phi(-4a) & 1\ 4\ 4^2 & 4^3 & 4^4 & 4^5 \\ \Delta\Phi(-5a) & 1\ 5\ 5^2 & 5^3 & 5^4 & 5^5 \end{vmatrix},$$

TABLE IV

FIRST VERTICAL DERIVATIVE COEFFICIENTS

For computing $\dfrac{\partial(\Delta\Phi)}{\partial z}$ on and below the plane $z=0$

(Grid interval=1 unit)

i	$\Delta\bar{\Phi}(r_i)$	$D'(r_i, 0)$	$D'(r_i, 1)$	$D'(r_i, 2)$	$D'(r_i, 3)$	$D'(r_i, 4)$
0	$\Delta\Phi(0)$	1.87282	6.62394	16.98074	36.11116	67.88049
1	$\Delta\bar{\Phi}(1)$	−1.13625	−5.62446	−16.05517	−35.96237	−69.68033
2	$\Delta\bar{\Phi}(\sqrt{2})$	−0.05949	0.12727	0.76135	2.17080	4.76651
3	$\Delta\bar{\Phi}(\sqrt{5})$	−0.30210	−0.88750	− 1.98701	− 3.83054	− 6.69004
4	$\Delta\bar{\Phi}(\sqrt{8})$	−0.05857	0.00361	0.23820	0.76745	1.74330
5	$\Delta\bar{\Phi}(\sqrt{13})$	−0.07597	−0.04856	0.09219	0.42646	1.05352
6	$\Delta\bar{\Phi}(\sqrt{25})$	−0.07072	−0.04007	0.07475	0.32573	0.77613
7	$\Delta\bar{\Phi}(\sqrt{50})$	−0.05758	−0.04575	− 0.00768	0.06859	0.19699
8	$\Delta\bar{\Phi}(\sqrt{136})$	−0.03905	−0.03615	− 0.02726	− 0.01084	0.01469
9	$\Delta\bar{\Phi}(\sqrt{274})$	−0.02286	−0.02233	− 0.02077	− 0.01812	− 0.01433
10	$\Delta\bar{\Phi}(\sqrt{625})$	−0.05020	−0.05000	− 0.04934	− 0.04832	− 0.04693

$$\left[\frac{\partial(\Delta\Phi)}{\partial z}\right]_{z=k} \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) D'(r_i, k)$$

TABLE V

SECOND VERTICAL DERIVATIVE COEFFICIENTS

For computing $\dfrac{\partial^2(\Delta\Phi)}{\partial z^2}$ on and below the plane $z=0$

(Grid interval = 1 unit)

i	$\Delta\bar{\Phi}(r_i)$	$D''(r_i, 0)$	$D''(r_i, 1)$	$D''(r_i, 2)$	$D''(r_i, 3)$
0	$\Delta\bar{\Phi}(0)$	2.82994	7.08408	14.15751	24.74755
1	$\Delta\bar{\Phi}(1)$	−2.49489	−6.93715	−14.51327	−26.02351
2	$\Delta\bar{\Phi}(\sqrt{2})$	0.05173	0.36265	0.96018	1.92719
3	$\Delta\bar{\Phi}(\sqrt{5})$	−0.39446	−0.80764	− 1.42970	− 2.30269
4	$\Delta\bar{\Phi}(\sqrt{8})$	0.00932	0.13050	0.35907	0.72474
5	$\Delta\bar{\Phi}(\sqrt{13})$	−0.00732	0.07231	0.22256	0.46253
6	$\Delta\bar{\Phi}(\sqrt{25})$	0.00304	0.06502	0.17330	0.33920
7	$\Delta\bar{\Phi}(\sqrt{50}$	0.00219	0.02312	0.05501	0.09985
8	$\Delta\bar{\Phi}(\sqrt{136})$	0.00040	0.00565	0.01239	0.02070
9	$\Delta\bar{\Phi}(\sqrt{274})$	0.00004	0.00103	0.00210	0.00322
10	$\Delta\bar{\Phi}(\sqrt{625})$	0.00000	0.00043	0.00085	0.00122

$$\left[\frac{\partial^2(\Delta\Phi)}{\partial z^2}\right]_{z=k} \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) D''(r_i, k)$$

which for $z=0$ agrees with Bickley's 6-point formula, and for $z=a$, $2a$, $3a$ takes the form

$$\left[\frac{\partial^2(\Delta\Phi)}{\partial z^2}\right]_{z=k} \approx \sum_{i=0}^{10} \Delta\bar{\Phi}(r_i) D''(r_i, k).$$

The second vertical derivative coefficients, $D''(r_i, k)$, are given in Table V. An inconsequential truncation error has been forced into the last row of coefficients of tables IV and V. Table VI shows the results obtained with these coefficients when used to compute the first and second vertical derivatives of the gravity anomaly of a sphere with center at (0, 0, 10), at various depths along the vertical axis.

TABLE VI

DERIVATIVE COEFFICIENTS TESTED ON GRAVITY ANOMALY OF SPHERE; CENTER (0, 0, 10), COMPUTED AT POINTS (0, 0, z)

Depth z	First Derivative, $\dfrac{\partial(\Delta\Phi)}{\partial z}$			Second Derivative, $\dfrac{\partial^2(\Delta\Phi)}{\partial z^2}$		
	True Value	Computed Value	Percent Error	True Value	Computed Value	Percent Error
0	125.0	126.2	1	187.5	191.5	2
1	171.5	173.9	1	285.8	275.9	3
2	244.1	238.6	2	457.8	391.1	15
3	364.4	331.4	9	780.9	543.0	30
4	578.7	458.6	21	—	—	—

Because differentiation weakens convergence, and tends to magnify errors in the original data, the derivative formulas should not be used with abandon at great depths.

COMPARATIVE RESOLVING POWER

Although the high resolving power of derivative methods is well known, it is instructive to compare the resolving power of the fields in terms of equivalent depths. Starting with the composite gravity anomaly of the two spheres discussed above, a central profile was computed for the various fields at various levels by the methods described in this paper. In order to have a common basis for comparison, the percent of maximum range of each anomaly was plotted in each case as shown in Figure 4. The field itself continued to the third, fourth, and fifth levels below the plane $z=0$ is shown on the right, together with the second derivative field for $z=0$ to $z=3$. On the left is the first derivative field at the indicated depths. For this case, it is apparent that the first derivative at $z=0$ has a resolving power equal to that of the field continued to $z=3$, but the first derivative itself must be continued to $z=3$ to have a resolving power equal to that of the second derivative at $z=0$. Derivative anomalies, unquestionably effective for resolution and for locating maxima, minima, and inflection points are otherwise

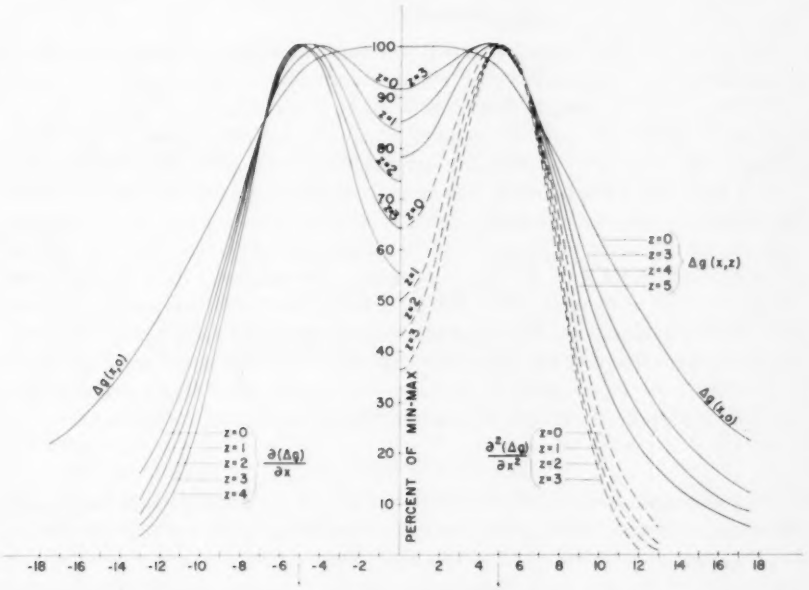

FIG. 4. Comparative resolving power of derived fields on and below the plane $z=0$. Composite gravity anomaly of two spheres; depth and horizontal separation of centers = 10 units.

something of an enigma to interpret. On the other hand, the field itself after downward continuation remains a perfectly good field to which a number of well-known interpretation techniques apply.

ELECTRONIC COMPUTER CALCULATIONS

The computation processes were programmed on Burroughs 205 and 220 computers by James Marsheck of the Computation Branch of the Geological Survey. The program follows the outline above with one exception—the sums of $\Delta\Phi$ on each circle are computed rather than the averages. The divisor which converts the sum to an average is incorporated in the coefficient. Gridded field data on punched cards are fed into the computer, which proceeds to sum $\Delta\Phi$ on the ten rings about each grid point. The sums are stored on magnetic tape and are thus immediately available for whatever type of field calculation is desired. The various sets of modified coefficients also are stored on magnetic tape. For a required calculation, the appropriate set of coefficients is called up and the computer cumulatively multiplies the coefficients and the ten-ring sums, and prints out the values by co-ordinates. Near the boundaries of the area the values become erratic because the program arbitrarily inserts null values on those portions of rings external to the area.

PRACTICAL TESTS

As pointed out by Nettleton (1954), the successful application of a process to simple theoretical anomalies by no means assures success when applied to practical field data. The system described here, however, has been successfully applied to a number of practical complex anomalies for which there is multilevel control. For example, consider the aeromagnetic map over the Mexican Hat Area of Utah, shown in Figure 5. The measurements were made with an AN/ASQ-3A flux-gate type magnetometer, flown at 8,500 ft above mean sea level, along lines spaced about one mile apart. These data were used to compute the field at the 6,000-ft level (Figure 6), for comparison with observed data on that level (Figure 7). The mesh interval is 2,500 ft; however, for better contouring we computed intermediate points by migrating the grid laterally one half step. The computations were done on the electronic computer. The computed anomaly faithfully reproduces the features of the observed anomaly, including a magnetic feature which correlates with the structural axis of the Raplee anticline.

ACCURACY

Objectionable oscillations sometimes occur in fields continued downward. When examined in profile under controlled conditions, these oscillations are seen to be about some mean value of the field. They are not inherent—rather they are symptomatic of a mesh that is too fine. By doubling or trebling the mesh interval, and computing intermediate points if necessary, one can eliminate the oscillations. The burden of smoothing, therefore, is made to rest upon the grid

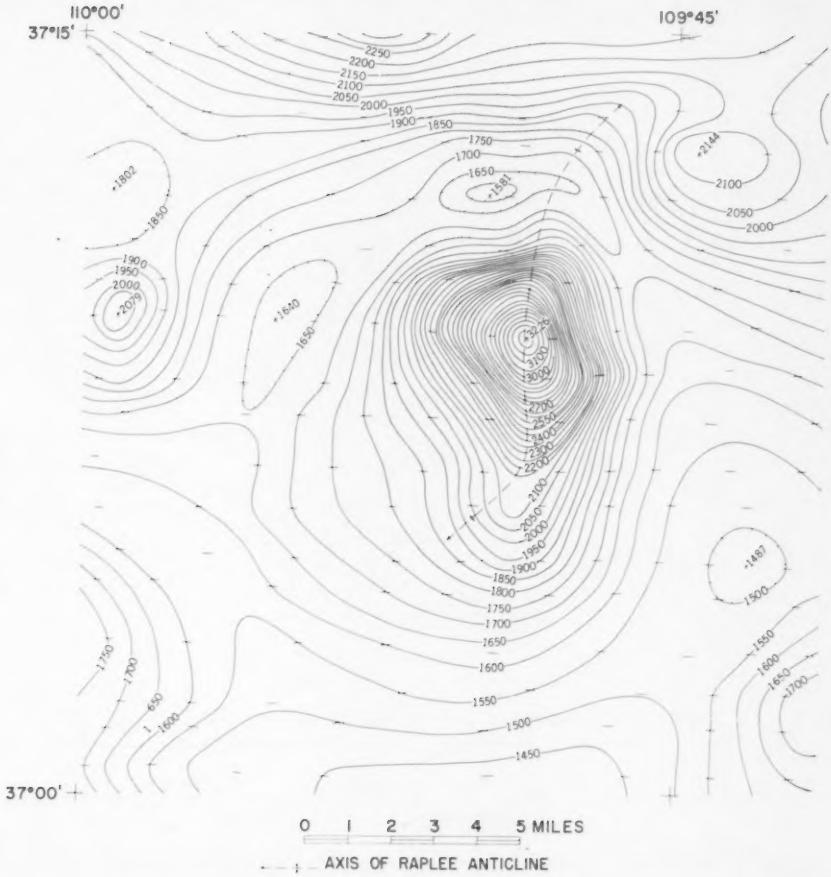

FIG. 5. Aeromagnetic map Mexican Hat area, Utah, observed at 8,500 ft above mean sea level; contour interval 50 gammas.

spacing, thereby obviating the introduction of arbitrary smoothing factors in the formulas. Any doubts about grid spacing can be resolved by a preliminary calculation of a few critical points on a desk calculator.

The extent to which a derived field satisfies the Laplace equation is perhaps the best criterion of the accuracy of the field. This test is troublesome to apply. The most practical check on derivative calculations is to use the derivative values in a Taylor expansion type of downward continuation—the continuation process used by Peters (1949). Three level data, e.g., $\Delta\Phi(0, 0, 0)$, $\Delta\Phi(0, 0, a)$ and $\Delta\Phi(0, 0, 2a)$ are required for this test. Neglecting terms of fourth order and higher we have

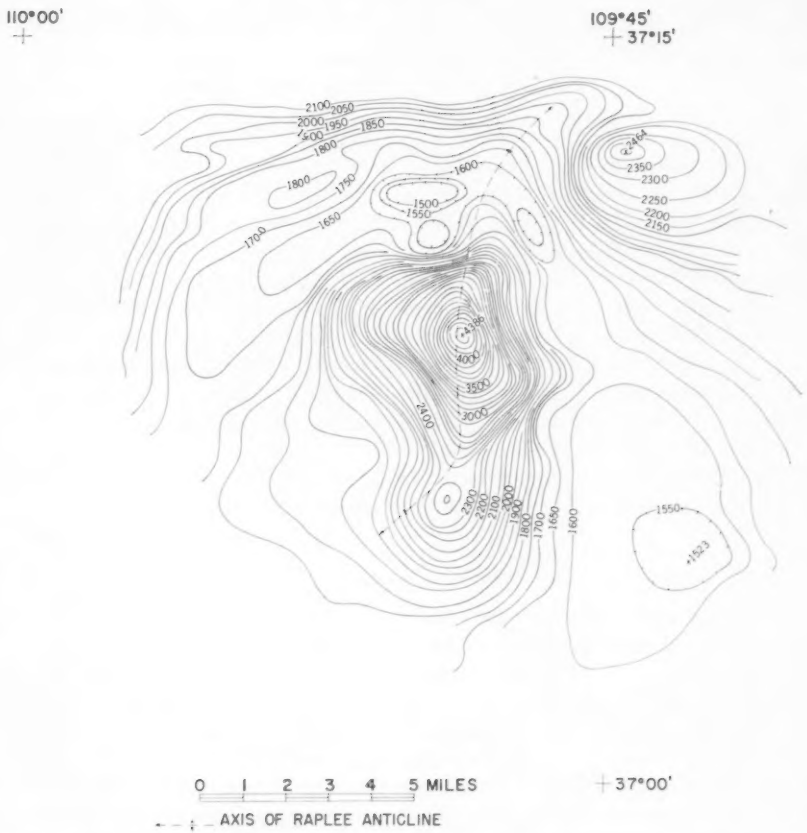

FIG. 6. Aeromagnetic map Mexican Hat area, Utah, computed at 6,000 ft above mean sea level from observed data at 8,500 ft; contour interval 50 and 100 gammas.

for $a=1$

$$\Delta\Phi(0,0,2) \approx 2\Delta\Phi(0,0,1) + \left[\frac{\partial^2(\Delta\Phi)}{\partial z^2}\right]_{z=1} - \Delta\Phi(0,0,0), \tag{8}$$

for checking second derivatives computed on the first level below the plane $z=0$.

In studying second derivative anomalies in Southeast Missouri, John W. Allingham of the Geological Survey found glaring discrepancies between values calculated from the D'' coefficients of this paper and those calculated on the same level from a standard second derivative formula which was thought to be quite good. For example consider the data of Table VII, computed for a given

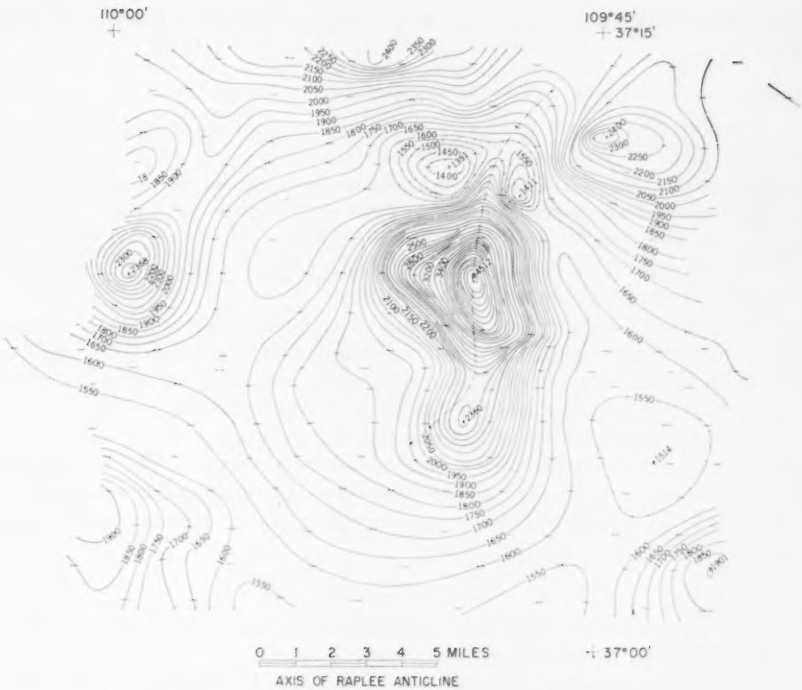

FIG. 7. Aeromagnetic map Mexican Hat area, Utah, observed at 6,000 ft above mean sea level; contour interval 50 and 100 gammas.

point on the Potosi, Missouri aeromagnetic map. There is a discrepancy between second derivative values computed for this point by the old and by the new formulas. When these derivative values are used in formula (8) to compute to the next lower level, field values of 4,693 γ and 3,510 γ are obtained for a point

TABLE VII

EXAMPLE OF USE OF TAYLOR EXPANSION TO RESOLVE DISCREPANCIES IN DERIVATIVE VALUES

Level z	Value of field $\Delta T(0, 0, z)$ in gammas	Value of $\frac{\partial^2 \Delta T}{\partial z^2}$ in gammas/(grid unit)^2 Old Formula	Value of $\frac{\partial^2 \Delta T}{\partial z^2}$ in gammas/(grid unit)^2 New Formula
0	2601		
1	2938	1418	235
2	3514	ΔT (0, 0, 2) from (8) 4693 γ	ΔT (0, 0, 2) from (8) 3510 γ

whose value is 3,514 γ. Clearly, the discrepancy is resolved in favor of the new formula.

CONCLUSIONS

Magnetic and gravity anomalies can be continued downward with an accuracy adequate for most purposes if careful attention is given to the details of the numerical analysis. When the continuation distance exceeds one half the depth of burial for tabular bodies, or one half the depth to the center for spherical bodies, the error can be expected to exceed ten percent. Downward continuation can aid interpretation for depth by bringing normally intractable anomalies within the compass of well established methods.

Those interested in resolving anomalies without altering the basic properties of the field might employ downward continuation to advantage. Those seeking the ultimate in resolution might find derivatives computed at depth preferable to higher derivatives computed on the plane of observations.

The various fields discussed in this paper are consistent to the extent that they have been derived from the same fundamental formula. The various sets of coefficients can be incorporated in high speed digital computer programs, or they can be used on desk calculators to compute profiles across interesting features.

ACKNOWLEDGMENTS

The author acknowledges his indebtedness to Frank W. Reilly, formerly with the Geological Survey, and to Donald B. Rock, and James Marsheck for computer programs and computations; to William J. Dempsey for providing the Mexican Hat aeromagnetic anomaly maps; to Alphonso Wilson for assistance in computations and for compilations; and to other personnel of the Geological Survey who have employed the methods described herein, thereby contributing to the experience gained in their use.

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GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 586–601, 11 FIGS.

BASEMENT MAPPING WITH AEROMAGNETIC DATA—BLIND RIVER BASIN*

NELSON C. STEENLAND† AND ROBERT J. BROD†

ABSTRACT

A detailed aeromagnetic map at 1,700 ft of 16 sq mi of the uranium-producing Blind River Basin of Ontario, Canada, shows anomalies interpreted to originate from shallow basic intrusives and deeper basement rocks. The identification of a major basement fault from a basement anomaly is described after demonstrating the isolation of these anomalies from the intrusive rocks on the basis of calculations of their depths. An aeromagnetic map computed upward to 2,630 ft and two second vertical derivative maps confirm the identification of the two categories of anomalies. Later drilling tends to confirm the existence of the fault.

The entire study is considered applicable to much larger aeromagnetic surveys because all types of anomalies are present within this small area where they can easily be correlated with their origins.

INTRODUCTION

Aeromagnetic maps are used extensively in exploration for petroleum for the primary purpose of calculating the thicknesses of the sedimentary section. The underlying rock is referred to as "basement," and aeromagnetic data are generally effective in determining this basement-sedimentary interface because basement ordinarily has much larger magnetic polarization than sediments. (Vacquier, et al., 1951, Chap. II esp.)

Often, but not necessarily, this interface is the top of the Precambrian, and it is mapped over thousands of square miles in the course of exploration for oil and gas. Basement mapping with aeromagnetic data in the Blind River Basin is quite different for two reasons. First, both basement and sediments are Precambrian. But this presents no difficulty because the sediments apparently have values of magnetic polarization representative of the more common, younger sediments and because the underlying basement is also typically magnetized. Secondly, the area is relatively very small, 16 sq mi. However, it contains all the problems that might be encountered in a large area. By surveying it in great detail, the very complex magnetic field is mapped with satisfactory precision.

THE PROBLEM

The Blind River Basin of Ontario, Canada, is located immediately north of Lake Huron. The basin currently is producing more than 30,000 tons of uranium ore daily from conglomerates at or near the base of the Precambrian sediments. Figure 1 shows the area of the survey in inset and in relationship to the basinal margins as indicated by the outcrop of the basement rocks. The ore is mined

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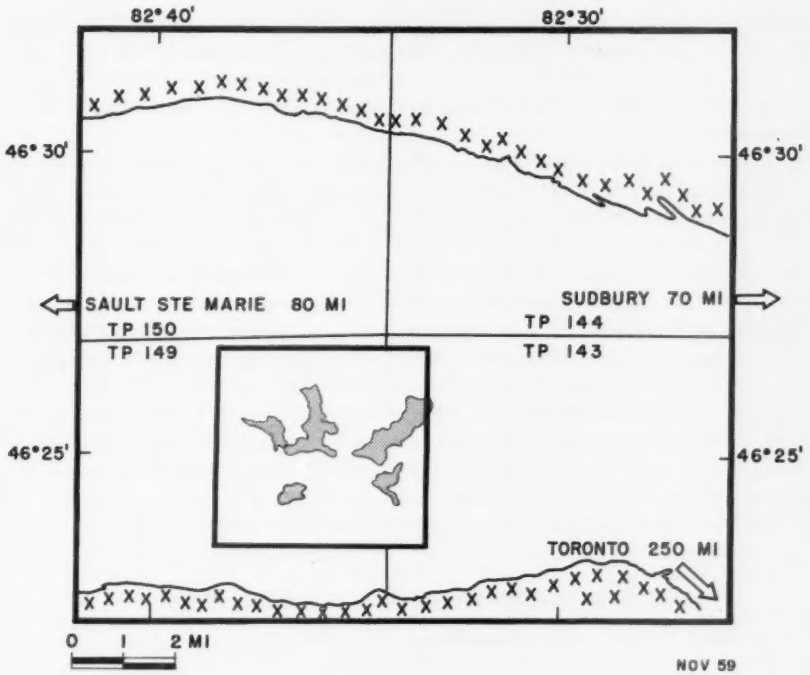

FIG. 1. Index Map showing basement outcrop on basinal margins.

primarily from shallow ore bodies along the margins of the basin, ore bodies delineated in 1956, ore having been first detected on outcrop in late 1953.

The aeromagnetic survey results from efforts by Stancan Uranium Corporation, discoverer of the Stanrock ore body, to delineate additional ore reserves in the deeper, central areas. There is no control of mineralization by basement structure or composition. However, knowledge of the basement's configuration is of great economic importance in the matter of locating deep diamond drill holes, a costly but the only successful method of finding these ores. With accurate information in hand with regard to the basement, consideration can be given to depth, in order to get as high as possible within a prospective area, and to faulting because of the difficulties involved in drilling shattered ground.

The authors acknowledge the permission of Stancan Uranium Corporation to publish this material.

GEOLOGY

The area typifies shield terrane with abundant outcrop. Collins' (1925) early studies are remarkably in agreement with the new information disclosed by the

recently accelerated activity. Roscoe (1956) provides the most recent stratigraphy of the area under discussion. Robertson and Steenland (1960) add perhaps the most detailed data on the uraniferous mineralization and subsurface conditions inasmuch as their work incorporates results from over 300,000 ft of diamond drilling.

The sequence of sediments in the Cobalt and Bruce series is shown in Table I.

These sediments, predominantly quartzites but with some limestone, shale, and conglomerate, attain a maximum thickness of approximately 5,100 ft in the area under discussion. This is considered to be the maximum thickness in the area between the productive areas on the northern and southern rims.

The sediments have a general synclinal attitude along an east-west axis, but this general picture is abruptly distorted by strike- and tear-faulting which appears to intensify from north to south. Metamorphism is low grade, the greenschist facies. Superimposed on earlier phenomena is a general soaking with sulphide. Pyrrhotite, chalcopyrite, sphalerite with occasional galena, and pyrite occupy fractures in all rocks from basement to the youngest Huronian sediments. What is important, however, is that no magnetic effects from these sediments are found in the aeromagnetic data.

The basement includes metamorphosed volcanics and sediments with acid

TABLE I

STRATIGRAPHIC SEQUENCE SHOWING RELATION OF VARIED TERMINOLOGY

Nomenclature of Collins		Nomenclature of Roscoe		Common Terminology	
Formation	Series	Group	Formation		
Lorraine	Cobalt			Lorraine quartzite	Upper Huronian
Gowganda		Dunlop	Gowganda	Gowganda conglomerate	
Serpent	Bruce	Quirke	Serpent	Serpent quartzite	Middle Huronian
Espanola			Espanola	Espanola limestone	
				Espanola greywacke	
				Bruce limestone	
Bruce			Bruce	Bruce conglomerate	
Mississagi		Mississagi	Ten Mile	Upper Mississagi quartzite	Lower Huronian
			Whiskey	Middle Mississagi argillite	
		Elliot	Nordic	Lower Mississagi quartzite conglomerate	
			Matinenda		

and basic intrusives of varying ages. These rocks are commonly considered to be of Archean (Precambrian) age. The Precambrian Huronian sediments overlie them with distinct unconformity.

Superimposed on all is a multitude of basic intrusives, diabases, both sills and dikes. Most intrusives are elongated along the basinal strike and reach shallow, if not outcrop, level. These rocks have large magnetic polarizations which cause conspicuous anomalies on the observed field.

THE AEROMAGNETIC SURVEY

The survey is made with a Gulf flux-gate magnetometer (Wyckoff, 1948), measuring essentially the total intensity of the earth's magnetic field (Vacquier, et al., 1951, p. 45 esp.), flown at an elevation of 1,700 ft above sea level. This affords a mean terrane clearance of approximately 500 ft. The area of greatest interest, the central portion of the survey, has flight lines oriented north-south and spaced 250 ft apart. This spacing increases to 500 ft south of the area of maximal interest. This system of lines is crossed by east-west lines spaced 1,000 ft apart. The entire area is approximately 16 sq mi.

A reproduction of an original magnetic record is shown in Figure 2, a north-south line. It is a typical record and an interesting one, showing the prominent anomalies from the basic intrusives obscuring the effect of the basement fault.

THE OBSERVED AEROMAGNETIC FIELD

The observed aeromagnetic field can only be incompletely represented here. Figure 3 shows it with contouring intervals of 20 and 100 gamma on an arbitrary datum. The observed data are adequate for contouring with even a two-gamma interval, if a large scale could be employed, because the survey is that accurate and detailed with respect to the observed anomalies.

All subsequent maps will be within the same outline and will show the major lakes as areas of reference. The lake just to the left of center, somewhat resembling the British Isles in shape, is Crotch Lake. The large lake with northeasterly attitude in the eastern part of the figure is McCabe Lake.

The observed magnetic field is dominated by an area of low intensity striking northwesterly across the area. This low is on the northeastern flank of a corresponding positive axis which has its highest intensity along the southern boundary of the map. This primary distribution of intensity is disturbed by sharp, narrow anomalies whose positive portions are always to the south of less developed, negative components. The most continuous example of the restricted type of anomaly is the positive axis extending westerly across the northern portion of the map.

THE DIABASE EFFECTS

The correlation between the areas of outcropping basic intrusives and the sharp, narrow anomalies demonstrates immediately the origin of these anomalies.

Moreover, these anomalies are sharp because the diabasic bodies invariably are near or on the surface. Depth estimates (Vacquier, et al., 1951) in every instance give values approximately at ground level. Figure 4 illustrates the correspondence between outcropping diabase and areas interpreted from the magnetic data to be underlain at shallow depths by similar materials. The great complexity of the

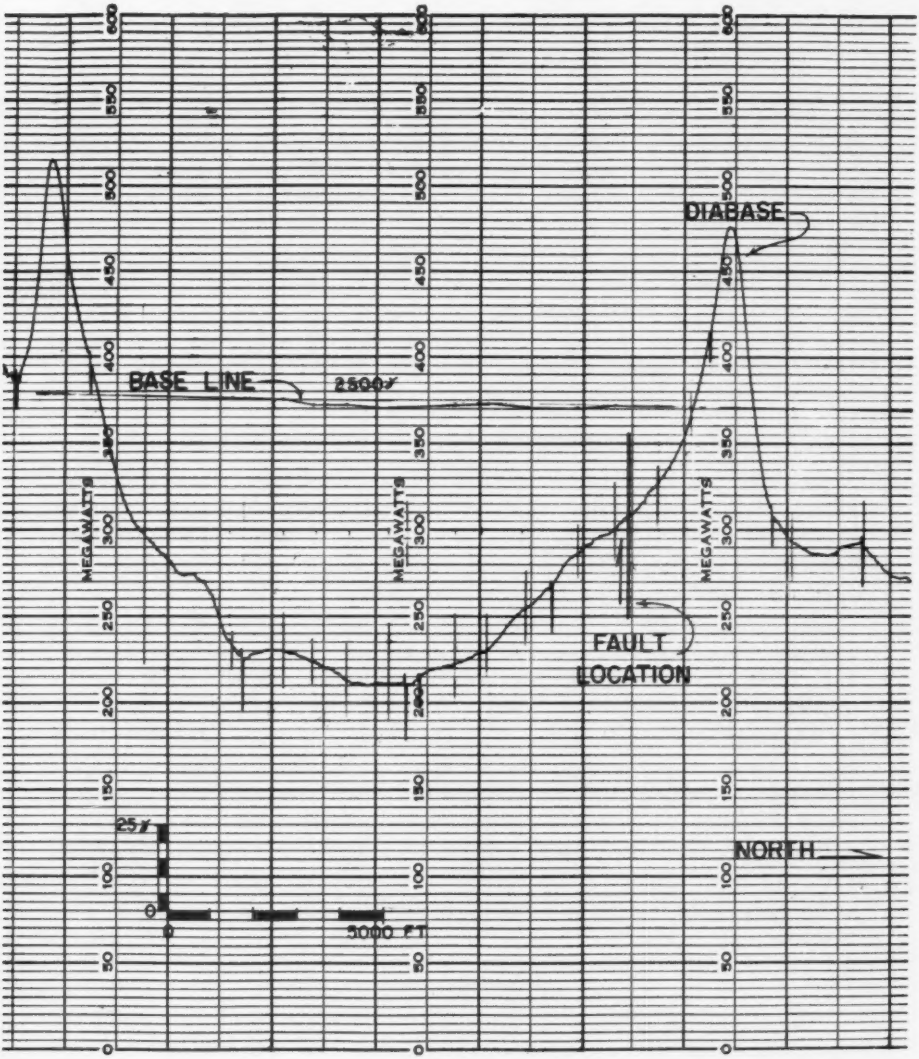

FIG. 2. Typical aeromagnetic record including location of major up-to-the-south basement fault.

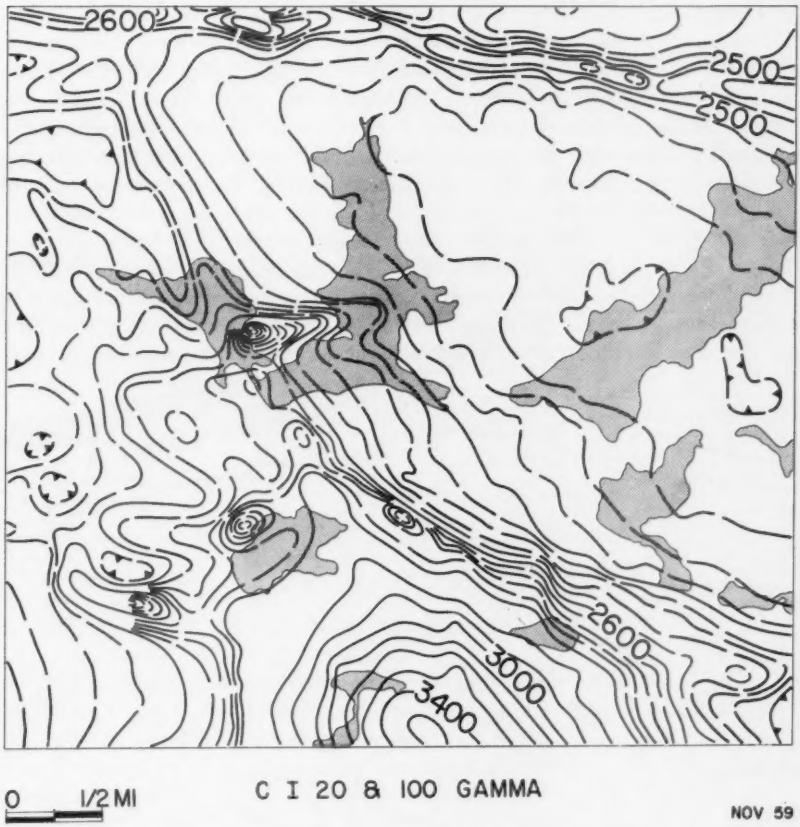

FIG. 3. Observed Aeromagnetic Map at 1,700 ft asl.

magnetic anomalies prohibits the development of more detail within the general zone, but it does include most of the diabase that crops out. The exception in the northwest is perhaps representative of the fact that many of these intrusives are so far into the quartzitic phase that they are undoubtedly weakly magnetic, if at all (Robertson and Steenland, 1960).

These anomalies are so abundant on the original flight-line records that they cannot all be represented on Figure 3. It is, of course, imperative to remove them with utmost accuracy before analyzing the magnetic data for effects of basement rocks. The difference in depth between the diabasic and basement rocks is sufficient to isolate anomalies from the former by depth computations made on the original magnetic tapes. Such anomalies yield depths at or near the surface, 500 ft below the survey.

Figure 5 illustrates the type of anomaly which has to be removed. The section, "A" of Figure 4, also shows the quantitative relationship between this anomaly and the subsurface in an area where the subsurface is well identified. The section is along a north-south line, and the anomaly under consideration is clearly observable in the southeastern corner of Figure 3, where it shows as a prominent eastward positive nose. The residual anomaly has an amplitude of 85 gamma. The underlying geologic section shows that this anomaly occurs over the southern flank of the basin where the basement and the sediments dip northward at approximately 20° on outcrop, decreasing to approximately 5° basinward. The diabase dike both crops out and is drilled through by diamond drill hole Z-5-1. A second drill hole, Z-5-2, north of 5-1 and farther basinward, is bottomed in granite without having intersected the diabase. The sediments in this section are the basal formation of the Huronian; the Lower, Middle, and Upper mem-

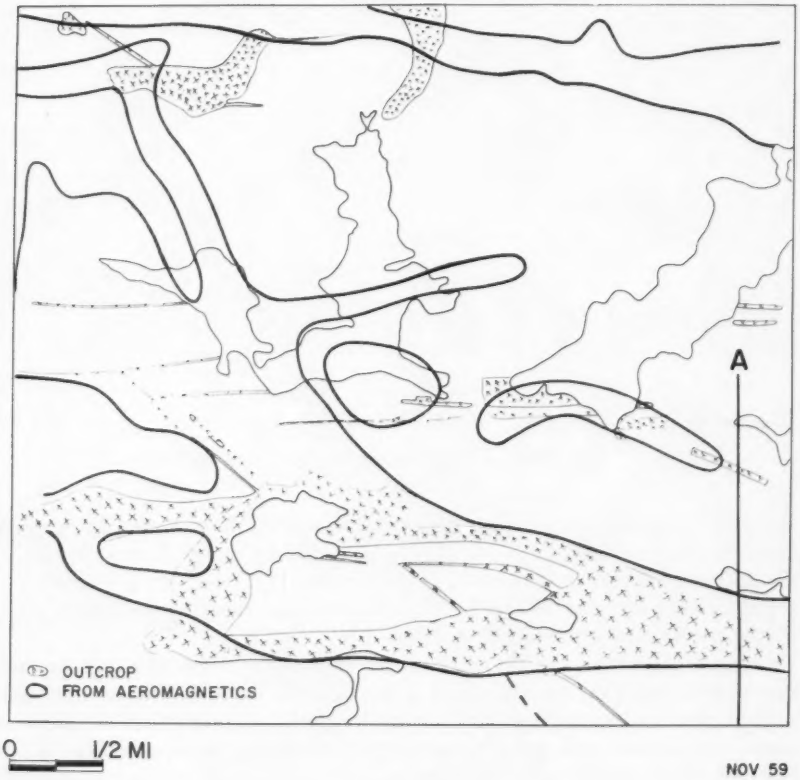

FIG. 4. Diabase Map.

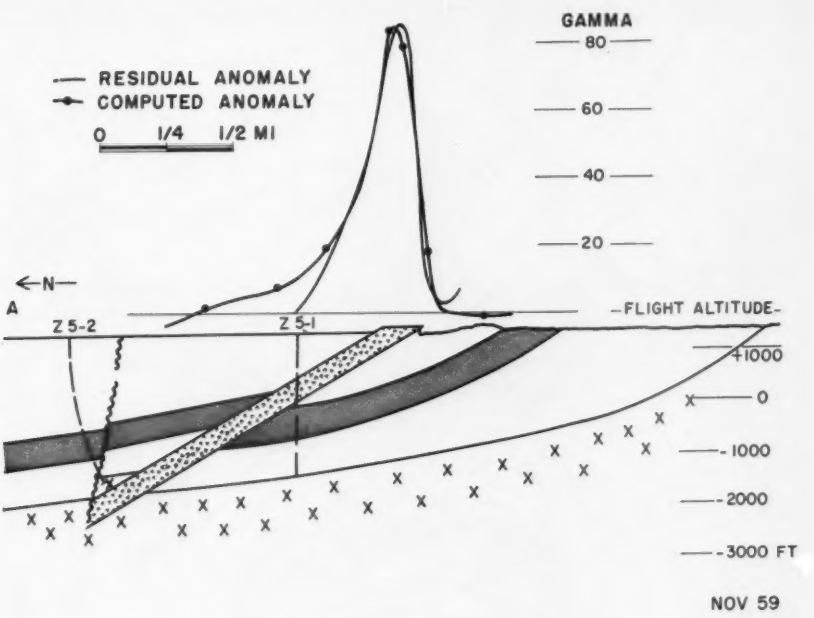

FIG. 5. Magnetic-Geologic Section A.

bers of the Mississagi formation. The Upper and Lower members are primarily quartzites; the Middle member is a rather pure argillite. As a matter of interest, the uranium bearing conglomerates occur as lenses in the Lower Mississagi either immediately on or not far above the surface of the basement. The anomaly is computed with the assumption that the polarization is normal and the susceptibility contrast is 600×10^{-6} emu. The agreement between the computed and residual anomalies is more than adequate to identify this type of anomaly with the intrusive bodies which are common throughout the basin.

THE BASEMENT AEROMAGNETIC MAP

The basement aeromagnetic map (Figure 6) is the field which results from the removal of the anomalies identified with the intrusives from the observed aeromagnetic map (Figure 3). Thus, it is the map of anomalies originating from the pre-Huronian basement. It shows the primary northwesterly trending positive and negative axes of the areas of high and low intensity without the sharp, conspicuous, east-west, "diabasic" anomalies of the observed map.

The authenticity of this map and, conversely, the reliability of the identification and removal of the diabase effects, may be investigated by computing the observed aeromagnetic field upward inasmuch as such a procedure should result

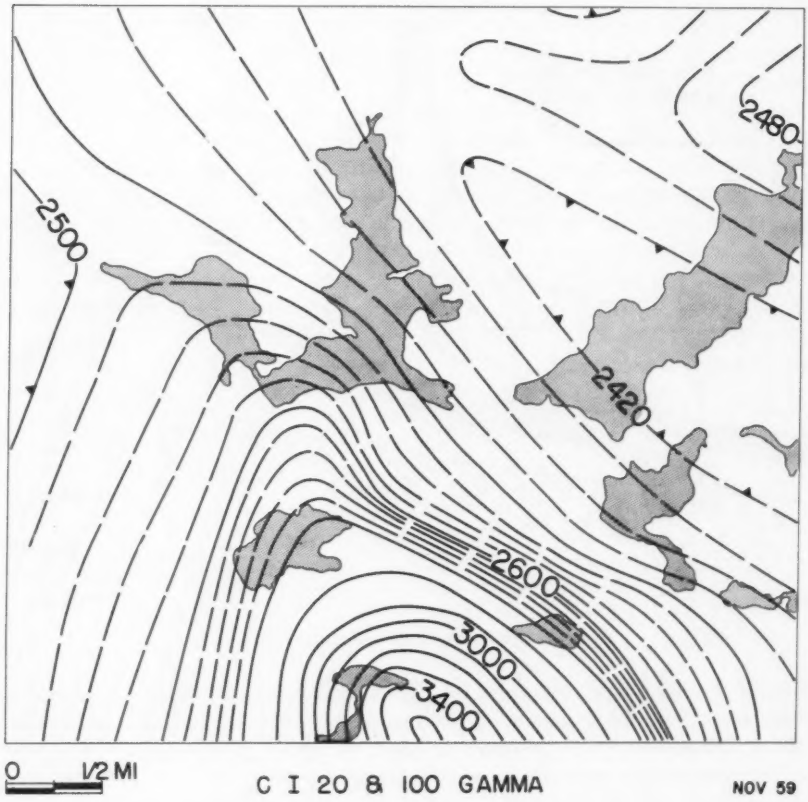

FIG. 6. Basement Aeromagnetic Map.

in the rapid attenuation of the diabasic effects compared to the basement effects.

Figure 7 is the computed aeromagnetic map at 2,630 ft above sea level, 930 ft above the original map. It is considered an excellent confirmation of the first attempt to produce a basement magnetic map because it not only confirms the primary areas of high and low intensity, it also confirms the negative area along the northern margin and the sharp, positive nose in the northeastern corner of Figure 6. The maps are divergent in the northwest where the continuation map shows part of a positive anomaly which does not appear on the basement aeromagnetic map. Note that some diabasic effects have not disappeared from the observed field in the continuation process. The conspicuous remnant is the small, westward, positive nose in the southwest which is a remnant of not a single diabasic effect but two contiguous, sharp, positive anomalies which are easily

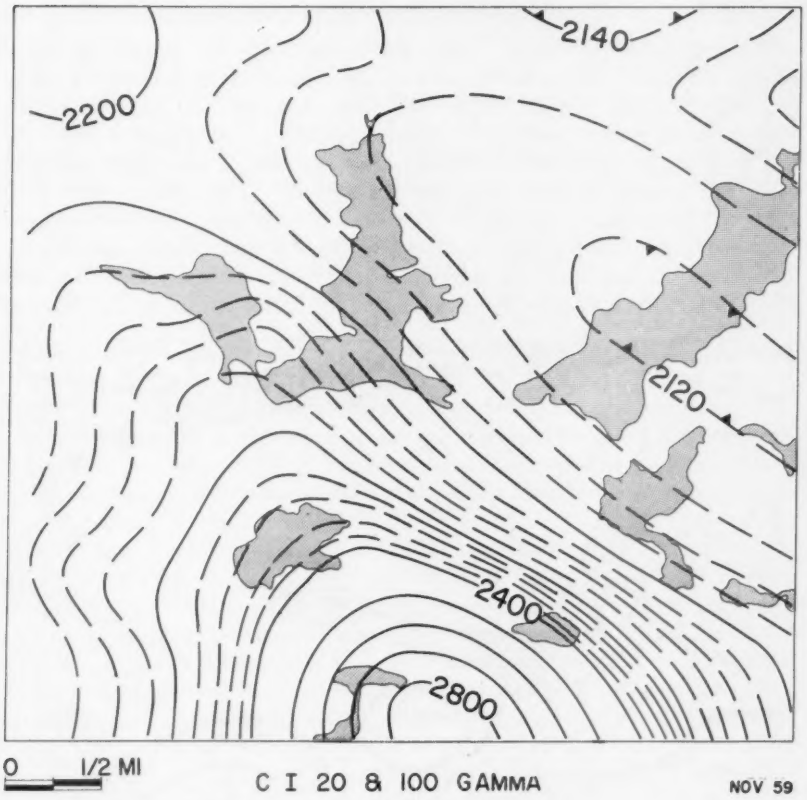

FIG. 7. Aeromagnetic Map at 2,630 ft asl.

discernible in Figure 3. The continuation is computed by the system published by Henderson and Zietz (1949), applied on a one-eighth mile grid. Note that the amplitude between high and low areas on the basement aeromagnetic map is almost 1,100 gamma. On the continuation map it is only 700 gamma.

It should be stated that the continuation map is really not helpful except for confirming the residual procedure used in correcting the observed aeromagnetic map for the diabasic effects. For example, to use the continuation map for basement depth computations is not as accurate as using the basement aeromagnetic map because points are known only every one-eighth mile on the continuation map. The control on the basement aeromagnetic map is essentially continuous inasmuch as the residual corrections are made from a close network of original flight tapes so that representation of the basement aeromagnetic field is continuously determined along each of the individual flight lines.

SECOND VERTICAL DERIVATIVE MAPS

Another technique for the isolation of anomalies is the use of the second vertical derivative. There are many formulas published for the application of this procedure, but it is well known that the results are essentially dependent upon grid size rather than the particular formula selected. Figure 8 shows the results of computing a second vertical derivative with a one-eighth mile grid using the formula of Henderson and Zietz (1949). The contour interval is $2{,}000 \times 10^{-15}$ cgs units. This map is computed directly from the observed aeromagnetic map. It shows that the basement effects are diminished and that the diabasic effects dominate this derivative field. As one illustration of this, note that depth computations made by measuring the distance from the zero contour

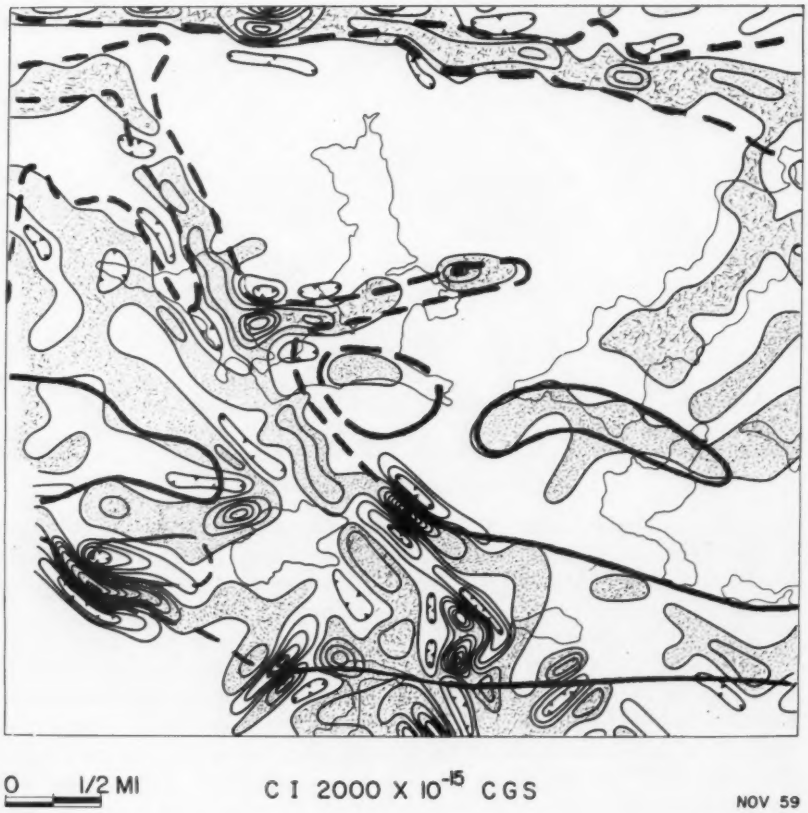

FIG. 8. Second vertical derivative from 1/8 mi grid with positive anomalies stippled. Outlines of diabase areas selected from aeromagnetic data are solid where confirmed by outcrop.

to the center of the positive anomaly are all of the order of 500 ft, the height of the survey above ground. Further illustration of the correlation of these derivative anomalies with diabases is brought out by superimposing on the derivative map the outline from Figure 4 of the areas of diabase selected from the original aeromagnetic data. This outline is solid only where confirmed by outcrop. An excellent example of the correlation between derivative features and diabase occurs along the positive trend in the northern portion of the map. Besides its being obvious that there are no anomalies which could be correlated with basement effects, there is an unusual feature of this map, the fact that all anomalies have approximately the same width. Perhaps this is another indication of the artificiality of a derivative calculation of this type inasmuch as it would be naive to assume that all intrusive bodies, if these are correctly identified as the sources of these anomalies, are exactly the same width throughout the area.

Figure 9 is the second vertical derivative computed with the same formula but using a one-mile grid. Although the one-mile grid is used, points are computed every one-eighth mile so that the map has the same number of control points as the map in Figure 8 computed with the one-eighth mile grid. The outlines selected from the aeromagnetic data as areas of diabase are shown as before to indicate their relationship to the anomalies. In this instance, only some of the diabasic effects are represented by derivative anomalies, particularly those in the northern portion of the map. However, the map does show some basement effects. For example, the positive axis on the southern boundary is the derivative expression of the strong observed positive anomaly in the south of Figure 3. A depth estimate on the flank of this anomaly is approximately $-1{,}600$ ft which is several hundred feet lower than the true depth of $-1{,}300$ ft. In conclusion, the use of the one-mile grid for the derivative calculation results in anomalies which are from both sources, the shallow intrusive rocks and the deeper basement rocks. One might say, therefore, that this map is more correctly representative of the derivative field of the original observed aeromagnetic field than the map made with the one-eighth mile grid. As such, it does not separate one group of anomalies from the other. As a matter of fact, it hardly serves to isolate one group of anomalies from another any more than they are isolated on the original observed map.

DISCUSSION

The original problem of mapping the surface of the basement is attacked by means of the original flight line tapes, on which the corrections are made for the diabasic effects, and by the basement aeromagnetic map (Figure 6) which shows the anomalies considered to arise from the basement. Depth computations made with these two sources of data are shown in hundreds of feet in Figure 10. Other data shown on this map are basement depths known from deep diamond drill holes and from the mineshafts themselves. These are shown in feet, posted next to the basement intersection points. Two of these points of intersection are shown with a circled dot indicating that these originate from deep diamond drill

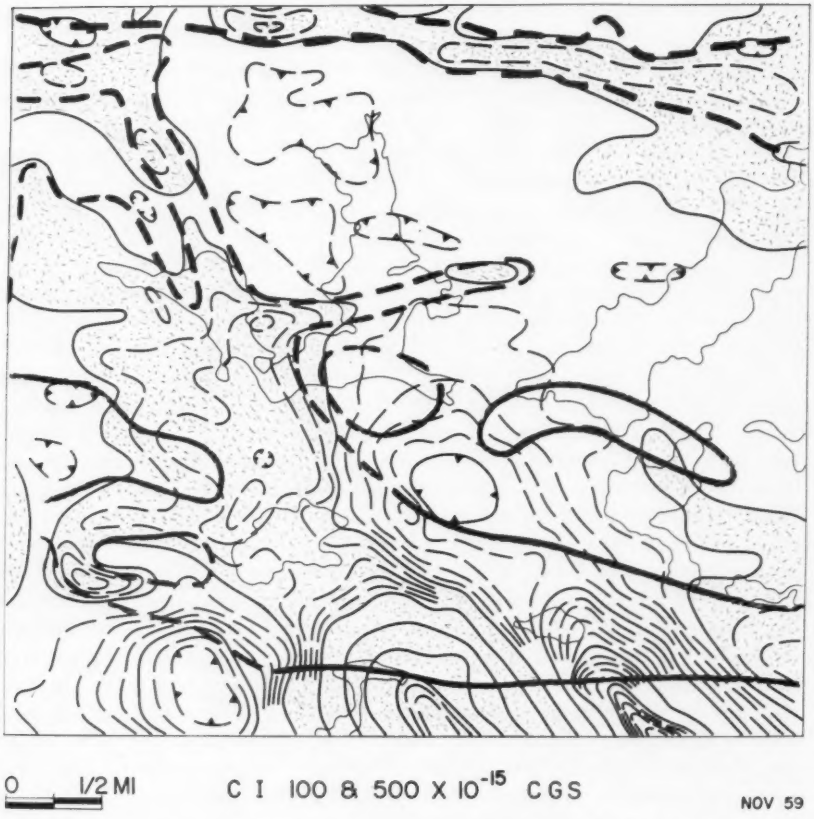

FIG. 9. Second vertical derivative from 1-mi grid with positive anomalies stippled. Outlines of diabase areas selected from aeromagnetic data are solid where confirmed by outcrop.

holes drilled after the original preparation of this basement map. The deepest diamond drill hole, no. 1 that with a depth of −3,900 ft estimated, is bottomed in the top of the Lower Mississagi because of mechanical failure. The fault shown between this hole and the one to the southwest bottomed at −2,338 ft, C2-4, is picked entirely from the aeromagnetic data and is interpreted to be a thrust fault. At the same time, two normal faults, also deduced from the aeromagnetic data, are shown in Figure 10. Furthermore, the computed depth estimates are used to contour the basement surface along with the known subsurface points at a 500 ft interval. The northward-dipping, southern flank of the basin is relatively uniform down to −2,000 ft, but the −2,500 ft contour noses abruptly into the basin in conjunction with the major thrust block. A drill hole, C2-5,

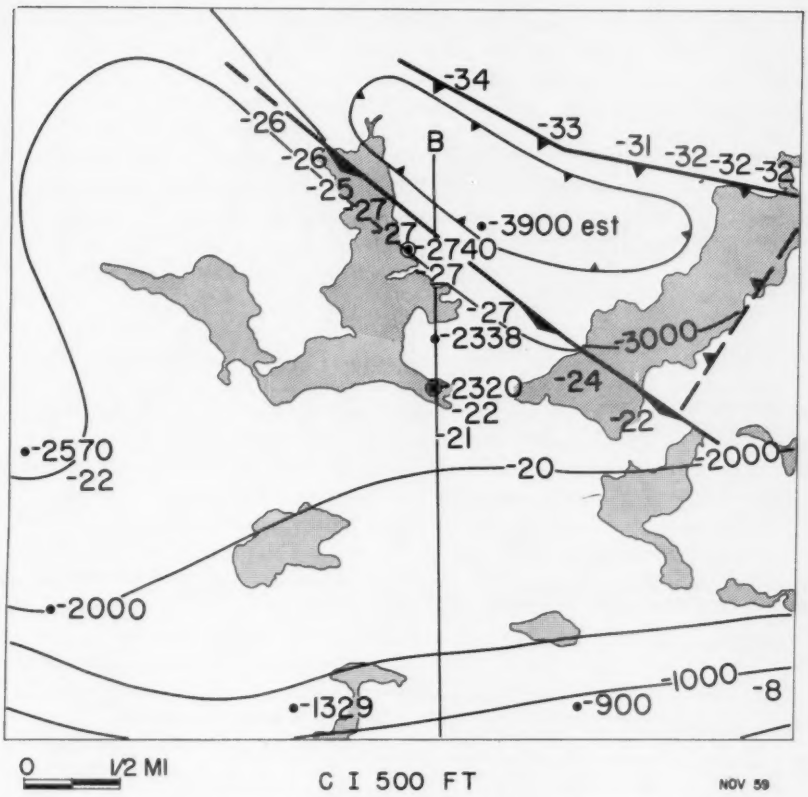

FIG. 10. Basement Map with basement depths computed from aeromagnetic data shown in ft/100 and subsurface basement "tops" in ft.

subsequently located on the eastern shore of Crotch Lake at a point between the two original drill holes, is bottomed on basement at −2,740 ft at a point flanked by two −2,700 ft computed depth estimates. Furthermore, another hole, C2-7, drilled on southern Crotch Lake, has a basement "top" of −2,320 ft immediately north of a computed depth estimate of −2,200 ft.

Figure 11 is a study of the magnetic expression of the fault, itself, in relation to the large observed aeromagnetic anomaly, undoubtedly of intrabasement origin, upon whose northern flank the fault anomaly occurs. The location of this section, "B," is shown on Figure 10. The large observed anomaly of Figure 11 is reproduced directly from the north-south flight line. Along with it is plotted a computed intrabasement effect to represent the large positive anomaly of the observed data. Notice that this computed effect matches the observed anomaly

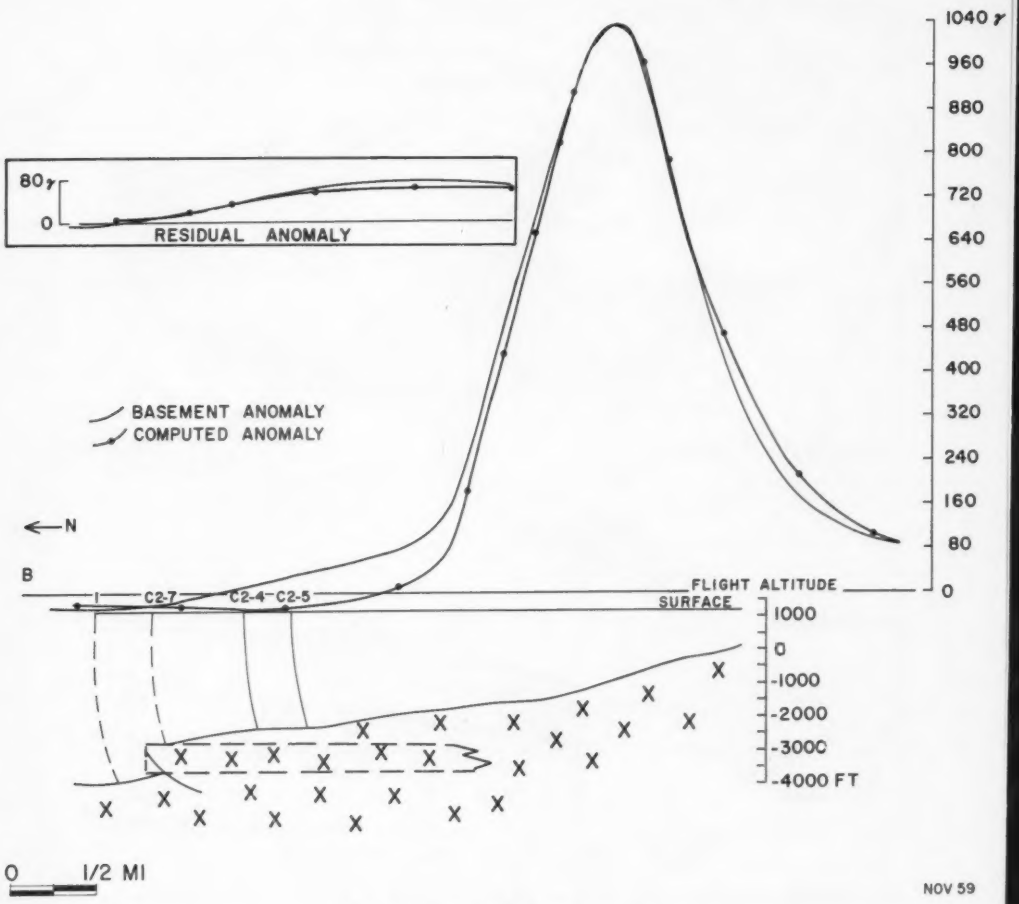

FIG. 11. Magnetic-Geologic Section B.

very closely south of the apex, even identically in the critical area immediately south of the apex. But north of the apex the computed effect has less amplitude throughout the extent of the anomaly until the curves join in the vicinity of the northern two drill holes. The difference between the two curves is an indication of a lack of conformity of the observed field to an intrabasement effect. Inasmuch as this entire field is considered to originate from the basement, the difference between the anomalies is quite probably the result of the fault. In addition to this matter of the difference between these two anomalies is the fact that the form of the observed northern limb of the anomaly does not fit an intrabasement

form. On the other hand, the form does fit that of a plate of material. The basement section is shown below the anomaly along with the four drill holes which give subsurface control on the basement surface. Superimposed on the basement is a hypothetical block used to represent the fault. The anomaly computed from this particular block is shown in the small inset on the upper left portion of the figure. This computed effect is compared with the residual effect or the difference between the observed and computed intrabasement anomalies. The residual has an amplitude of 75 gamma. A susceptibility contrast of $3{,}000 \times 10^{-6}$ emu is used in computing the curve to match the residual anomaly. The basement displacement is 880 ft with the upthrown block at $-2{,}740$ ft.

CONCLUSION

Perhaps this presentation has greater significance than simply demonstrating the applicability of the aeromagnetic method to a very small-scale problem in mining. A larger area of applicability is the relevance to the much larger and much more common problem of surveying sedimentary basins with the airborne magnetometer in connection with petroleum exploration. The relationship between the two subjects is a matter of scale. The survey under discussion has in it the three principal components which are encountered in the more conventional, large aeromagnetic surveys. These are, first, intrabasement effects; secondly, effects from the structure of the basement's surface; and, thirdly, the effects of intrusive and extrusive rocks. These are all here together with closely identified geologic conditions which can be correlated very directly and very quantitatively with these three components.

In the study of these relationships, procedures are utilized which are well documented in geophysical literature in order to demonstrate the applicability of procedures which are available to everyone.

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GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 602–612, 10 FIGS.

GEOPHYSICAL CASE HISTORY OF THE HORSE CREEK FIELD, LARAMIE COUNTY, WYOMING*

JACK W. PETERS†

ABSTRACT

The Horse Creek field located in Laramie County, Wyoming, was discovered and developed by the General Petroleum Corporation following a reconnaissance gravity survey and preliminary and detail seismic surveys. The gravity survey, made during 1940, delineated a strong maximum gravity anomaly having a magnitude of about 5 mg. Limited seismic work was then conducted in the area during 1941 and 1942 and mapped a prominent anticline having some 2,000 ft of closure. In September, 1942, General Petroleum Corporation spudded in their No. 78-31-G well, located on the apex of the structure. This well was completed as the discovery for the field, producing from the lower Cretaceous-Lakota sand. The second well, No. 74-6-P, was completed in April, 1943, as the lower Cretaceous-Muddy sand discovery for the field. Further seismic work was done during 1944 and 1945 to detail and refine the structural picture. Subsequent drilling developed the Muddy sand as the primary producing zone in this field. A total of 32 producing wells has been drilled on this structure and to August, 1958, the total cumulative production from the field was 3,519,000 barrels of oil.

INTRODUCTION

The Horse Creek field was discovered and developed by the General Petroleum Corporation and was the first oil field discovered in the Wyoming portion of the Denver-Cheyenne Basin. This field offers a rather ideal example of a geophysical case history in that the discovery was based entirely on geophysics and involved a logical sequence of reconnaissance gravity work followed by preliminary and detailed seismic work.

LOCATION AND GENERAL GEOLOGY

The Horse Creek field, located in Laramie County, Wyoming, is situated in the Denver-Cheyenne Basin about 20 miles northwest of the city of Cheyenne (Figure 1). Geologically, the Horse Creek field is situated on the steep west flank of the Denver-Cheyenne Basin, midway between the Precambrian outcrops on the Laramie Mountains ten miles to the west and the trough of the basin ten miles to the east. Surface beds over the field area are flat-lying Pliocene and Miocene beds. These beds form a prominent angular unconformity with the older formations and completely conceal the underlying structure.

GRAVITY SURVEY

The first indication of structure in the Horse Creek field area was furnished by a reconnaissance gravity survey which covered some 2,000 sq. mi. along the west rim of the Denver-Cheyenne Basin. This gravity survey was conducted by the Independent Exploration Company during the summer and fall of 1940 for Manning & Martin, Incorporated. Figure 2 shows that portion of the origi-

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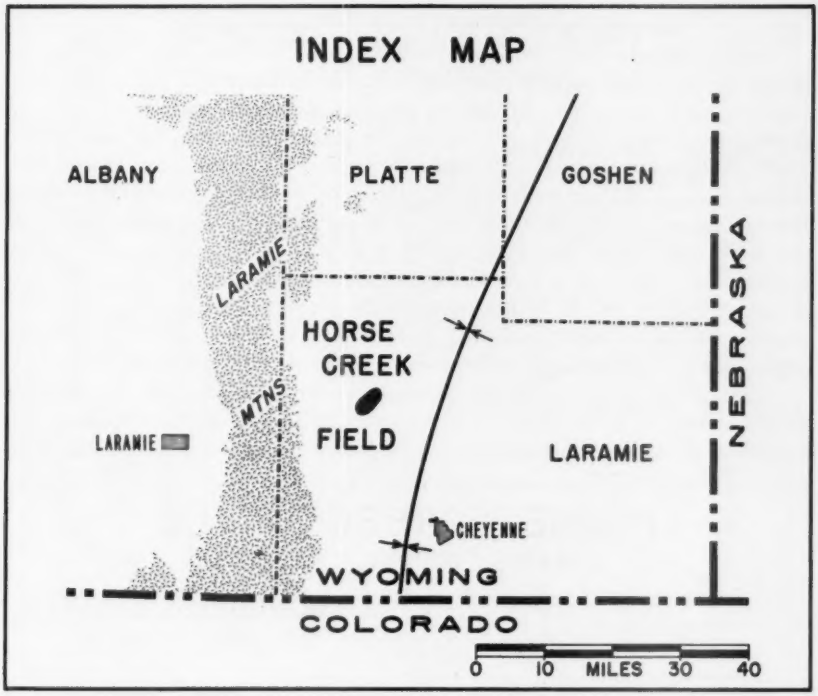

FIG. 1. Index map showing location of Horse Creek field. The trough of Denver-Cheyenne Basin is indicated by the synclinal axis. Precambrian outcrops of Laramie Mountains are shown by stippled areas.

nal gravity map which covers the Horse Creek field area. The contour interval on this map is one mg with every five-mg line emphasized. Gravity stations are indicated by small circles. This map shows a strong northeast-southwest trending maximum gravity anomaly having a magnitude of about 5 mg. For reference, the subsequent producing area of the Horse Creek field is shaded on this map and it shows favorable correlation with the observed gravity anomaly. To emphasize this favorable correlation, a residual gravity map was computed recently and is shown in Figure 3.

Mr. John H. Wilson of the Independent Exploration Company supervised the gravity survey and made the original interpretation of the data. In his report, he designated this anomaly in the Horse Creek field area as the outstanding anomaly in the survey and recommended it for further evaluation. On the basis of this gravity work, Manning & Martin acquired a 7,700 acre lease block on this gravity anomaly.

PRELIMINARY SEISMIC SURVEYS

During August, 1941, the General Petroleum Corporation took a geophysical option on the leases held by Manning & Martin in the Horse Creek field area with the right to conduct further geophysical operations and to acquire and develop the leases. Subsequently, during September-December, 1941, and June, 1942, the Western Geophysical Company, working for General Petroleum, shot several lines of dip correlations across the gravity anomaly and the optioned leases. The seismic map in Figure 4 is an interpretation of the preliminary seismic work made during July, 1942, by Mr. A. F. Barrett of the General Petroleum Corporation. This map is contoured on the lower Cretaceous-Dakota horizon at an interval of 500 ft. Shotpoint locations are shown by small circles. This preliminary seismic work, although quite limited, indicated a very prominent anticlinal structure possibly having some 2,000 ft of closure.

Figure 5 is an east-west seismic dip section across the structure. The location of this section is shown by line AA' on Figure 4. In this section, the wavy line represents the approximate unconformity between the relatively flat dip segments

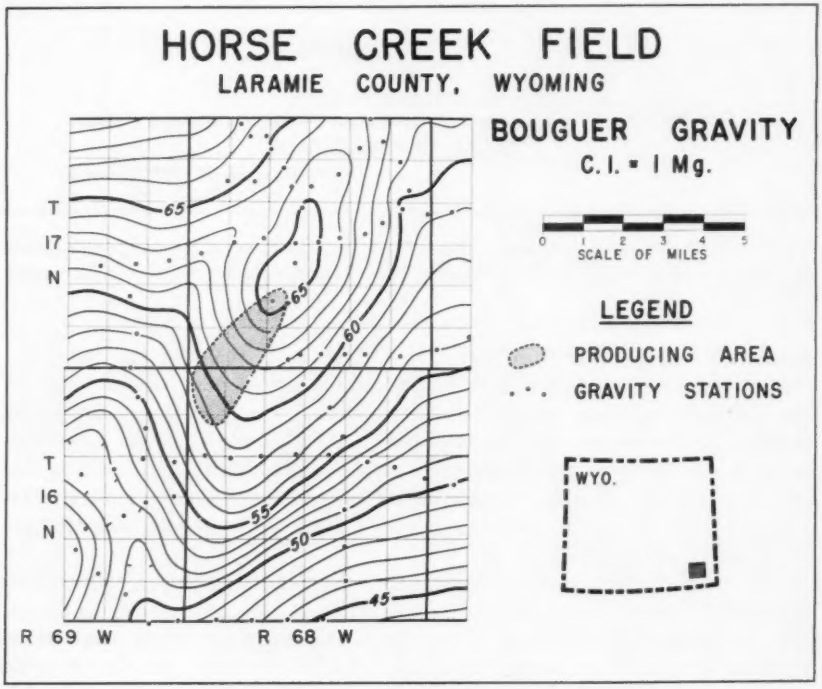

FIG. 2. Bouguer gravity map of the Horse Creek field area. Shaded area represents subsequent producing area of the field. Gravity station locations are shown by small circles. Contour interval is one mg.

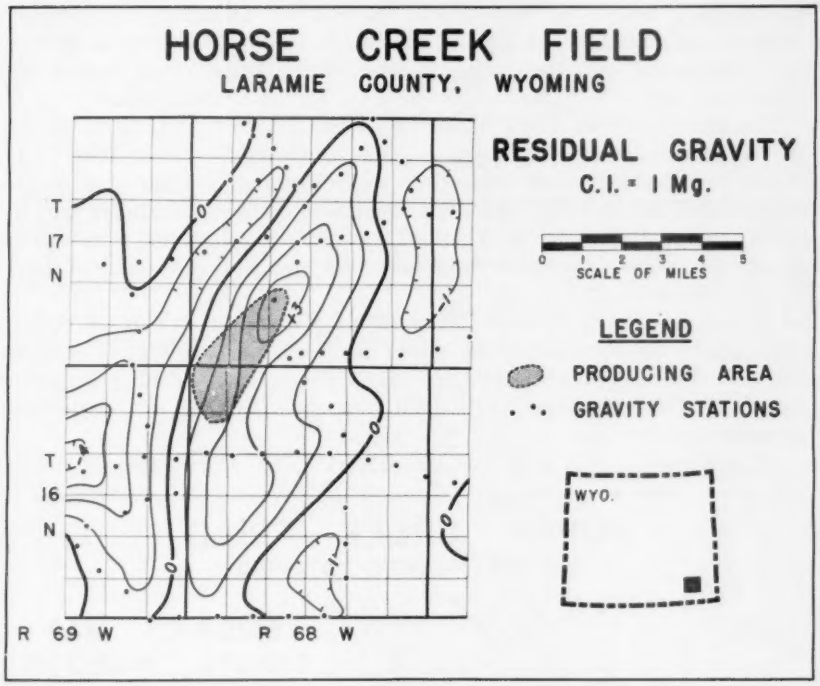

FIG. 3. Residual gravity map of the Horse Creek field area. Shaded area represents subsequent producing area of the field. Gravity station locations are shown by small circles. Contour interval is one mg.

in the overlying Tertiary section and the steeply dipping segments in the underlying Cretaceous section. The dashed line represents the phantom horizon used in making the preliminary seismic "Dakota" map.

On the basis of this preliminary seismic work, General Petroleum took assignment of the leases from Manning & Martin, and, with additional lease acquisitions, assembled a solid lease block of approximately 25,000 acres on this prospect.

DISCOVERY WELLS AND INITIAL DEVELOPMENT

In September, 1942, General Petroleum Corporation spudded in their No. 78-31-G well located on the apex of the seismic structure in SW SE SE sec. 31, T. 17 N., R. 68 W. (Figure 4). This well encountered oil saturation in two lower Cretaceous sands, the Muddy ("J") and the Lakota, and was drilled to a total depth of 5,530 ft into the Jurassic-Morrison formation. Drill stem tests recovered only a slight show of oil from the Muddy but indicated commercial production from the Lakota sand within the interval 5,490–5,530 ft. This well was completed

in November, 1942, as the discovery for the field with an initial daily pumping production of 455 bbl of 30° gravity oil and 114 bbl of water from the Lakota sand. Concurrent with the drilling at this well, a few additional lines of dip correlations were shot by Western on the south portion of the structure.

The second well, No. 74-6-P, located in SW SE NE sec. 6, T. 16 N., R. 68 W., one half mile south of the discovery, was spudded during November, 1942. Tests in this well indicated considerable fresh water with only a scum of oil in the Lakota sand, but recovered significant amounts of oil from the Muddy sand in the interval of 5,422–5,446 ft. This well was completed in April, 1943, as the Muddy discovery for the field with an initial daily pumping production of about 25 bbl of 34° gravity oil.

A third well, No. 32-32-G, located in SW NE NW sec. 32, T. 17 N., R. 68 W., three fourths mile northeast of the Lakota discovery, was completed in September, 1943. The Lakota in this well was "wet" with no shows of oil or gas and a test of the Muddy recovered only a slight scum of oil. This well was temporarily abandoned.

In September, 1943, a rig was moved back to the Lakota discovery well,

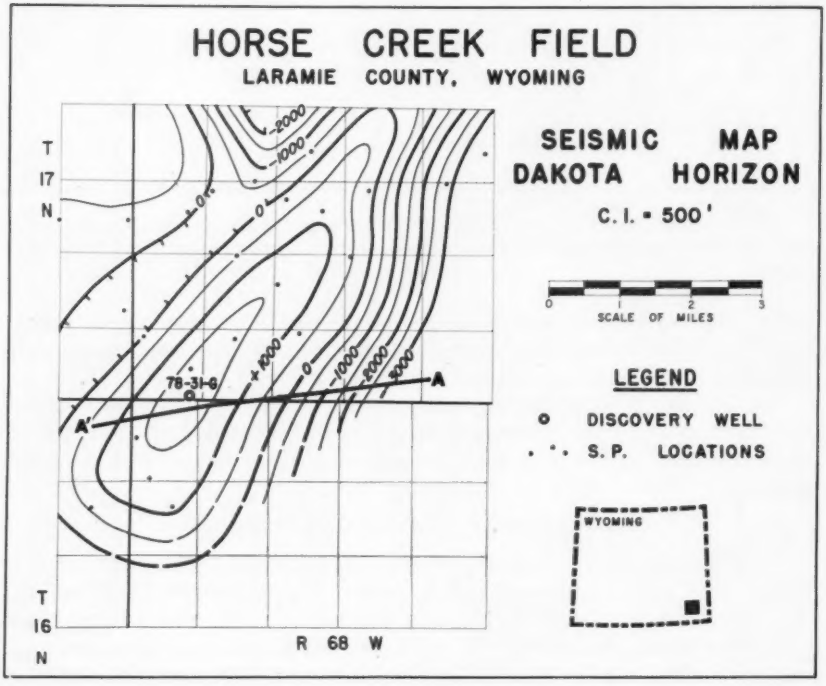

FIG. 4. Preliminary seismic map of the Horse Creek field area. Contoured on the lower Cretaceous-Dakota horizon. Contour interval is 500 ft. Shotpoint locations are shown by small circles.

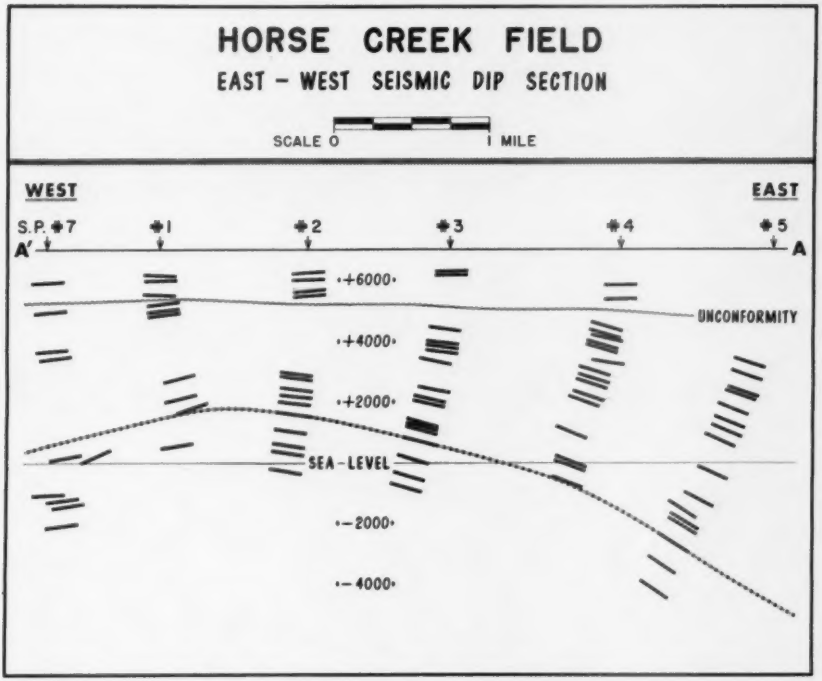

FIG. 5. East-west seismic dip section, *AA'*, across the Horse Creek structure. Vertical and horizontal scales are equal. Dashed line represents "Dakota" phantom horizon.

No. 78-31-G, to deepen this well and test the deeper production possibilities in the field. This well was deepened to 7,457 ft into the Pennsylvanian-Casper formation without encountering any oil saturation below the Lakota and was then plugged back and recompleted in the Lakota.

After completing these three wells, the outlook for the field was not too encouraging. Only two horizons, the Lakota and Muddy sands, appeared productive. The water cuts in the Lakota discovery well, No. 78-31-G, had increased to 80 percent, and the Muddy discovery well, No. 74-6-P, was averaging only about 15 bbl of oil per day. Also, the long and severe winters encountered at this 7,000 ft elevation restricted operations considerably. General Petroleum Corporation decided to suspend drilling operations pending further production tests and additional seismic work to detail and refine the structural picture.

DETAIL SEISMIC SURVEYS

The first of the detail seismic work, consisting of a few lines of continuous shooting across the apex of the structure, was done by Western Geophysical Company during May and June, 1944. The Independent Exploration Company

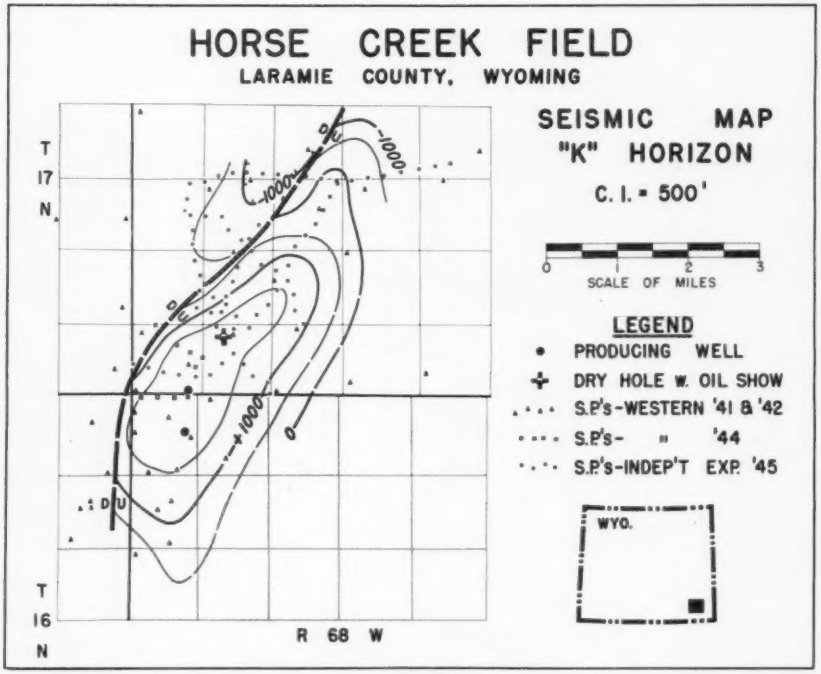

FIG. 6. Detail seismic map of the Horse Creek field area contoured on the "K" horizon (250 ft above Muddy). Contour interval is 500 ft. Shotpoint locations of different seismic surveys are shown by the various symbols.

then did some continuous seismic work on the north portion of the structure during September-December, 1945. A map compiling the detail and previous preliminary seismic work on the main portion of the structure was prepared in September, 1946, by Mr. A. F. Barrett and Mr. W. H. Hohag, Jr., both of General Petroleum Corporation, and it is shown in Figure 6. This map is contoured on the "K" horizon (250 ft above the Muddy) at an interval of 500 ft. Shotpoint locations of the different seismic surveys are shown by the various symbols. The three wells completed at this time are also indicated.

This map and several other interpretations of the data in this area, show faulting on the west flank of the structure. A throw of more than 1,000 ft is indicated in some interpretations. The presence of this fault is still debatable because the seismic data there is limited and of poor quality, and also because no wells have been drilled this far down on the west flank.

FINAL DEVELOPMENTS

Following this detailed seismic work and after some encouraging results were obtained in the extensive well work-overs and production tests, four additional

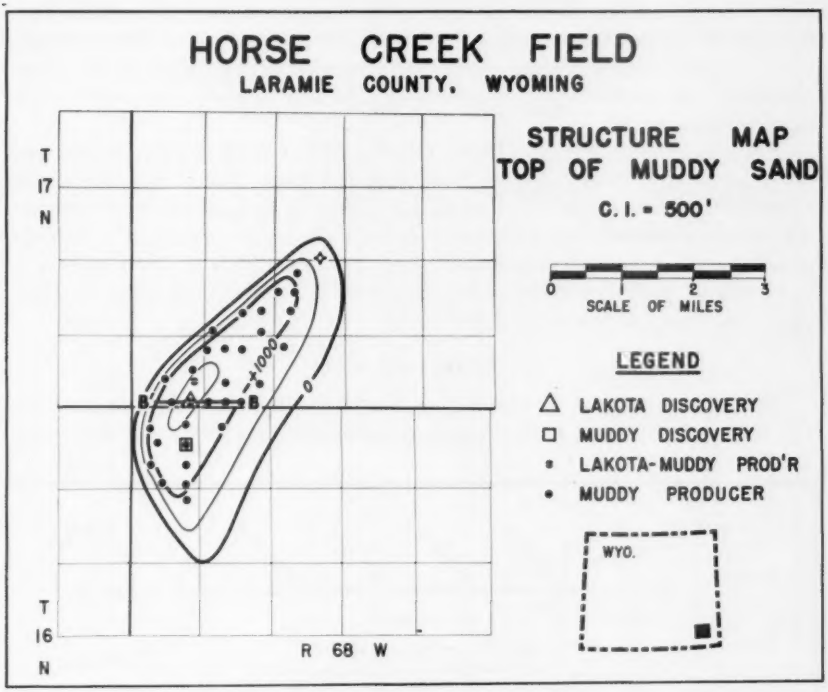

FIG. 7. Subsurface map of Horse Creek field based on well data. Contoured on top of Muddy sand at an interval of 500 ft.

field wells were drilled in 1947, seven in 1948, thirteen in 1949, and five in 1951; all by the General Petroleum Corporation. A map showing the locations of all the wells drilled on the structure is shown in Figure 7. This map was prepared by Mr. K. A. Gorton of the General Petroleum Corporation during 1951 and represents the structure on top of the Muddy sand based primarily on well data. The map is contoured at an interval of 500 ft. In all, General Petroleum drilled a total of 32 producing wells, all of which were ultimately produced from the Muddy sand. Two wells on the apex of the structure also produced from the Lakota sand, but the production from this sand was finally suspended and plugged off during 1946 and 1947 because of extremely high water cuts. One dry hole was drilled by Fred M. Manning, Incorporated during 1949, in SE SW SE sec. 21, T. 17 N., R. 68 W on the northeasterly plunge of the structure. No additional drilling has been done in this field since 1951.

Figure 8 presents an east-west electric log section across the apex of the structure. The location of this section is shown by line *BB'* on Figure 7. The General Petroleum No. 78-31-G well, which was the discovery well and which

was the deepest test in the field is shown in the central portion of the section. This well was drilled to a total depth of 7,457 ft into the Pennsylvanian-Casper formation. The approximate Tertiary-Cretaceous unconformity is shown in the upper portion of the section and the underlying structure is shown on various Cretaceous horizons.

Since January 1, 1953, the Horse Creek field has been included within the operational territory of the Mobil Producing Company, a sister company of the General Petroleum Corporation. In January, 1955, S. R. Faust of Mobil Producing Company reviewed all of the previous seismic work, incorporated it with the data from the wells, and prepared the map shown in Figure 9. The map is contoured on the Dakota horizon at an interval of 500 ft. This map indicates structural closure of approximately 2,400 ft.

PRODUCTION DATA

The chart in Figure 10 summarizes the production and reservoir data for the Muddy zone, the primary producing zone at this field. The peak production

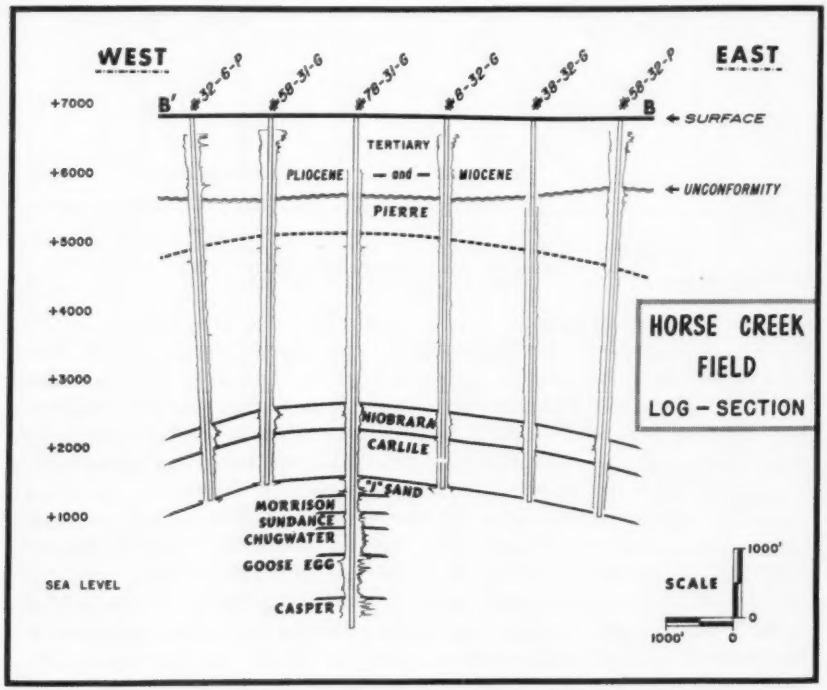

FIG. 8. East-west electric log section, *BB'*, across the Horse Creek field. Vertical and horizontal scales are equal.

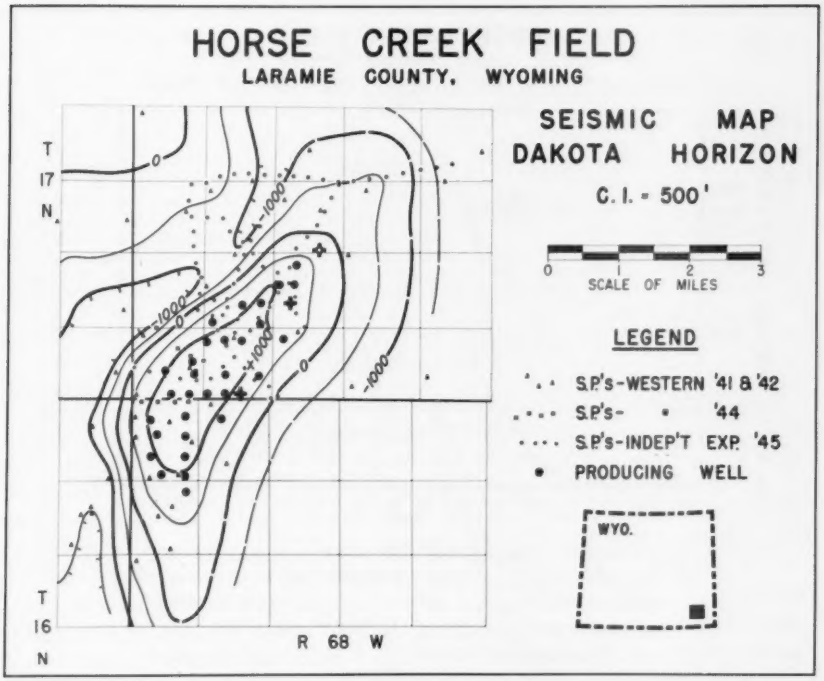

FIG. 9. Seismic map of Horse Creek field incorporating well data. Contoured on Dakota horizon at an interval of 500 ft. Shotpoint locations of different seismic surveys are indicated by the various symbols.

was obtained during the latter part of 1949, when the field was producing at an average rate of about 2,000 bbl of oil per day. Since then, the production has declined rather rapidly with the latest production rate being about 500 bbl of oil per day. Prior to 1949, the water rate in the field was negligible, but began to increase rapidly as edge wells on the east flank were drilled and produced. After abandoning two wells on the east flank in 1954, the water rate was reduced considerably.

The Muddy sand reservoir is a tight sand, approximately 25 ft in thickness with an average porosity of 13.5 percent and an average permeability of less than one millidarcy. Production mainly depends on a natural fracture system which exists in the tight sand.

Throughout the development and producing operations in this field, an extensive well stimulation program has been conducted in an attempt to improve the productivity of the wells. Of the various procedures used, oil squeeze and chemical-oil squeeze treatments were the most successful.

The oil squeeze treatments in 1948 produced remarkable results, increasing

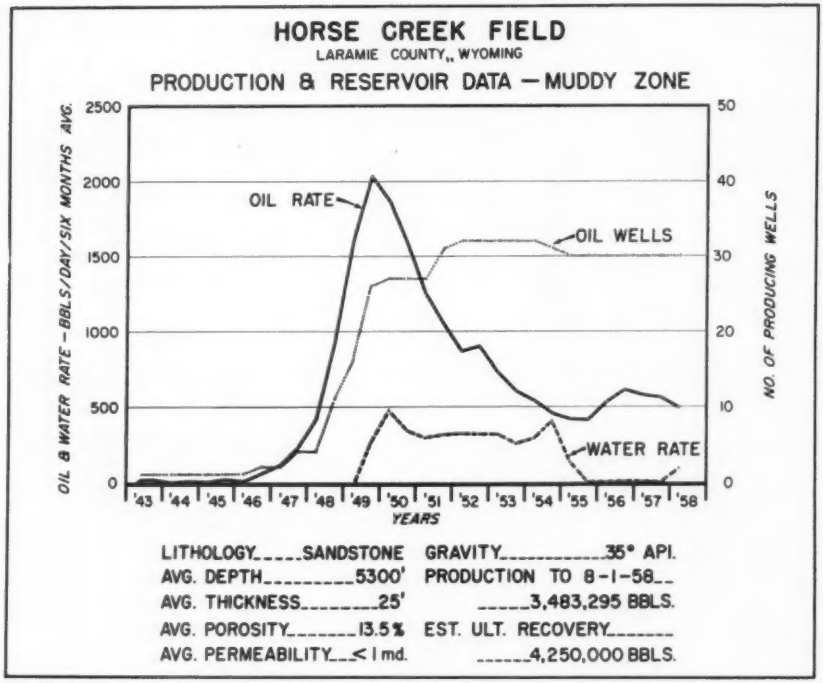

FIG. 10. Production and reservoir data of the Muddy zone, Horse Creek field.

the average daily production in several wells by about 140 percent. Beginning in 1956, chemical-oil squeeze treatments were performed on a group of wells and increased the average daily production in these wells by approximately 75 percent. The increase in field production shown in 1956 (Figure 10) was a result of these latter treatments.

As of August 1, 1958, the total cumulative production from the Horse Creek field was 3,519,000 bbl oil of which 3,483,000 bbl were produced from the Muddy sand and 36,000 bbl were produced from the Lakota sand. The total ultimate recovery from the field is estimated to be about 4,250,000 bbl.

ACKNOWLEDGMENTS

The author wishes to thank the General Petroleum Corporation and the Mobil Producing Company for permission to publish this paper. Special thanks is given to Mr. A. F. Barrett of the Mobil Producing Company and Mr. John H. Wilson of the Woodson Oil Company for providing much of the basic information and data.

GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 613–624, 5 FIGS.

USE OF RECIPROCITY THEOREM FOR COMPUTATION OF LOW-FREQUENCY RADIATION PATTERNS*

J. E. WHITE†

ABSTRACT

Starting with a simple word statement of the reciprocity which exists between forces and displacements in a general elastic solid, it is shown that low-frequency radiation of shear and compressional waves from relatively complex sources can be obtained by solving relatively simple problems in static elasticity. Illustrative examples include radiation from radial and tangential pairs of forces acting on the wall of a cylinder, pressure in a finite cylinder, and a pair of radial forces in a hole in a plate. For the last case, measurements in a plexiglas plate compare favorably with computations.

INTRODUCTION

Various forms of symmetry or reciprocity between sources and resulting disturbances have long been recognized in electromagnetic fields, elasticity, and acoustics, and the intimate relationship between source strength and receiver sensitivity for a reversible transducer has been described. Hence, it is to be expected that any attempt to compute the disturbance due to a particular source configuration should automatically raise the question, "Would it be easier to compute the behavior as a receiver and apply a reciprocity relation?"

In connection with a field program aimed at systematically measuring the speeds of shear and compressional waves in near-surface earth layers, the writer became interested in the radiation of elastic waves due to localized forces on the interior of a cylindrical borehole in an elastic solid. Since direct solution of the radiation problem seemed unattainable, attention was turned to the possibility of solving the problem in reverse, which would require then a reciprocity relation for elastic solids, explicit and quantitative.

Primakoff and Foldy (1947) proved that for two transducers of the same type coupled to an inhomogeneous, bounded, acoustical (fluid) medium, a statement like the following holds: If a current into one transducer causes an open-circuit voltage at the terminals of a second transducer, then the same current into the second transducer will cause an identical open-circuit voltage at the first transducer. To support the strong implication that this would apply also when the medium included elastic solids as well as gases or liquids, the rather extreme "medium" shown in Figure 1 was assembled. The first geophone is mounted on a pipe which rests on the bottom of a glass desiccator. The second geophone is attached to the glass with a chunk of modelling clay, below the water level. The top pair of traces shows the current into the first geophone and the voltage at the second; the bottom traces show the current in the second geophone and the

* Manuscript received by the Editor January 7, 1960.

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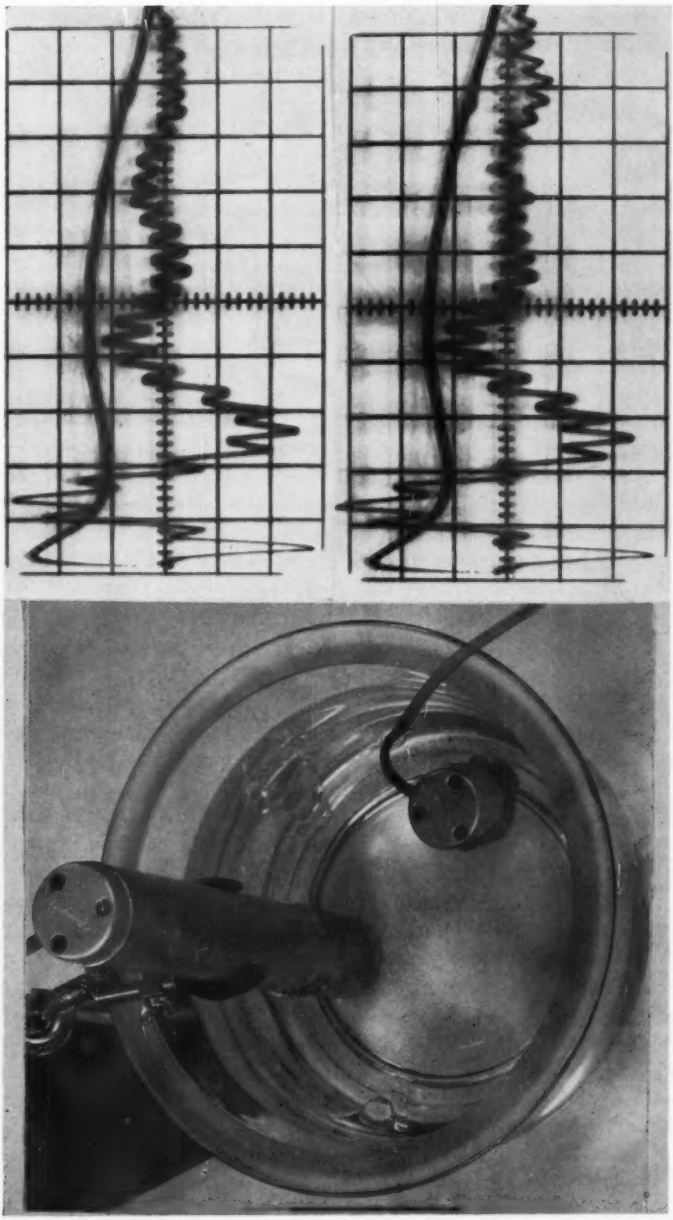

FIG. 1. Demonstration of reciprocity for "inhomogeneous elastic medium."

voltage at the first. This is convincing evidence that the reciprocity relation makes no stringent demands on the nature of the elastic medium. If the two transducers referred to above are small, light geophones imbedded in an elastic solid, an interesting conclusion can be drawn. When a current is fed into such a geophone, it will exert a localized force in the solid. The second geophone will move with the solid surrounding it, and an open circuit voltage will appear at its terminals which is proportional to the local particle velocity. If the roles are reversed, the force will be exerted at the second location and the velocity be sensed at the first. Hence, the above statement concerning transducers is entirely equivalent to a statement of reciprocity between force and particle velocity.

Morse and Feshbach (1953) discuss reciprocity conditions for elastic waves in an isotropic medium, but their notation is "compact," to say the least, and the application of their expressions to a particular case would require some further manipulation. Knopoff and Gangi (1959) show that a reciprocal relation between a point force and particle displacement holds for a bounded, inhomogeneous, anisotropic, elastic solid.

STATEMENT OF RECIPROCITY

Although none of the above writers makes the statement in so many words, their proofs certainly justify the following:

If, in a bounded, inhomogeneous, anisotropic, elastic medium, a transient force $f(t)$ applied in some particular direction α at some point P creates at a second point Q a transient displacement whose component in some direction β is $u(t)$, then the application of the same force $f(t)$ at point Q in the direction β will cause a displacement at point P whose component in the direction α is $u(t)$.

Note that the statement applies to the whole disturbance, whether it be body waves, surface waves, or whatever. It is not restricted to "far-field" geometry. The usefulness of this reciprocity condition will be demonstrated in the sections which follow.

METHOD OF APPLICATION

In each example treated here, the elastic solid is taken to be homogeneous and isotropic. The forces making up the source are in a small region: that is, the transit time across this region is short compared with the time required for an appreciable change in the transient disturbance; or, in steady-state terms, the dimensions of this region are small compared with the shortest wavelength of interest. Only the "far-field" radiation will be considered, that is, the particle displacement of the waves radiated into the interior of the solid.

With the source at the origin of spherical coordinates, the displacement at a distant point can be specified by the three perpendicular components u_r, u_θ, and u_ϕ. More explicitly, the collection of point forces making up the source, all of time dependence $f(t)$, will cause a radial displacement $u_r(t)$ at the observation point. The reciprocity relation states that if a radially-oriented point force $f(t)$

now acts at the observation point, the summation of displacements at the source points in the directions of the original forces will exactly equal u_r. The known solution for a point force, Love (1927), shows that the displacement at a point in line with the force is itself entirely in this direction also, the tangential components being zero, and it is recognized as a compressional wave.

$$u_c = \frac{1}{4\pi r \rho V_c^2} f(t - r/V_c). \tag{1}$$

This compressional wave can be described in terms of normal stresses; the displacements at the source due to these stresses computed; and the sum of the appropriate displacement set equal to u_r. In the far-field, plane wave relations apply approximately, and the normal stress in the direction of travel is,

$$N = \frac{1}{4\pi r V_c} f'(t - r/V_c). \tag{2}$$

A similar line of reasoning applies to either tangential displacement, u_θ or u_ϕ. The displacement at a point at a distance r perpendicular to the direction of the force is entirely tangential, consisting of a shear wave with displacement in the direction of the force,

$$u_s = \frac{1}{4\pi r \rho V_s^2} f(t - r/V_s). \tag{3}$$

This shear wave is accompanied by tangential stresses, from which displacements at the source can be computed, the sum of which equals u_θ (or u_ϕ). The tangential stress is given by

$$T = \frac{1}{4\pi r V_s} f'(t - r/V_s).$$

LOCAL FORCES ON CYLINDER WALL

The radiation patterns of many specific configurations can be obtained in very simple fashion by this procedure. For example, consider the angular dependence in a plane perpendicular to the cylinder of waves radiated by two oppositely-directed forces acting normal to the cylinder wall. The geometry is shown in Figure 2. By symmetry, there will be no shear wave with motion perpendicular to this plane. Hence, compressional waves and shear waves with motion in the plane will be considered.

To develop the radial motion of the cylinder wall due to a plane compressional wave, use is made of the relations, White (1953), that for a normal stress R along the cylinder axis, $l_r/a = -\sigma R/V$, whereas for a normal stress S perpendicular to cylinder axis, $l_r/a = (1+2\cos 2\theta)S/V$. In either case, a function representing translation or rotation of the whole body could be added to the expressions for radial displacement. A plane wave of normal stress N in the direction of travel is

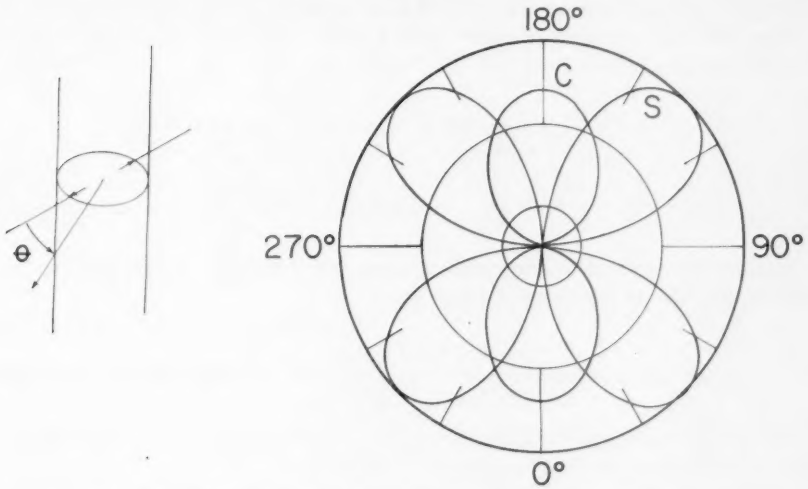

FIG. 2. Shear and compressional displacements due to radial forces in cylinder.

accompanied by a stress $N\sigma/(1-\sigma)$ in each of the two perpendicular directions. The total radial displacement due to these stresses is,

$$\frac{l_r}{a} = \frac{N}{Y}(1 + 2\cos 2\theta) + \frac{N\sigma}{Y(1-\sigma)}(1 - 2\cos 2\theta) - \frac{N\sigma^2}{Y(1-\sigma)},$$

or

$$\frac{l_r}{a} = \frac{N}{2\rho V_s^2}\left[1 + \frac{8(1 - V_s^2/V_c^2)V_s^2/V_c^2}{(3 - 4V_s^2/V_c^2)}\cos 2\theta\right]. \tag{5}$$

To this should be added the particle displacement accompanying the compressional wave. For two points located as shown in Figure 2 this bodily displacement exactly cancels, whereas the radial displacements at θ and $(\theta+180°)$ are seen to be equal. Hence, the desired sum of displacements equalling u_r is twice l_r. Putting in the value of N from equation 2,

$$u_r = \frac{a}{4\pi r\rho V_s^2 V_c}\left[1 + \frac{8(1 - V_s^2/V_c^2)V_s^2/V_c^2}{(3 - 4V_s^2/V_c^2)}\cos 2\theta\right]f'(t - r/V_c). \tag{6}$$

This is the radial displacement at a distance r due to a pair of radial forces at the ends of a diameter of a cylinder.

In computing the shear wave radiated by this pair of forces, use is made of the fact that a shear stress of magnitude T such as would accompany a shear

wave from direction θ can be thought of as a normal stress of magnitude $-T$ at $(\theta+45°)$ plus one of magnitude $+T$ at $(\theta-45°)$. Hence the radial displacement due to the shear stress T is,

$$\frac{l_r}{a} = \frac{T}{Y}\left[1 + 2\cos 2(\theta + 45°) - 1 - 2\cos 2(\theta - 45°)\right]$$
$$\frac{l_r}{} = \frac{-4T}{Y}\sin 2\theta. \tag{7}$$

Without repetition of the intermediate steps, the transient displacement in the shear wave due to two opposite forces is,

$$u_\theta = \frac{a(1 - V_s^2/V_c^2)\sin 2\theta}{\pi r\rho V_s^3(3 - 4V_s^2/V_c^2)} f'(t - r/V_s). \tag{8}$$

This is the tangential displacement at a distance r from a pair of radial forces on the wall of a cylindrical cavity.

The compressional and shear displacements are plotted in Figure 2, with V_s^2/V_c^2 set equal to $\frac{1}{3}$. Note that the compressional wave exhibits a "reverse break" phenomenon, that is, for a small angular range near 90°, the sign of the motion is opposite to the sign in the main lobes.

Consider the application of two local forces applied at the ends of a diameter and acting tangentially to the wall, as shown in Figure 3. It will be sufficient to

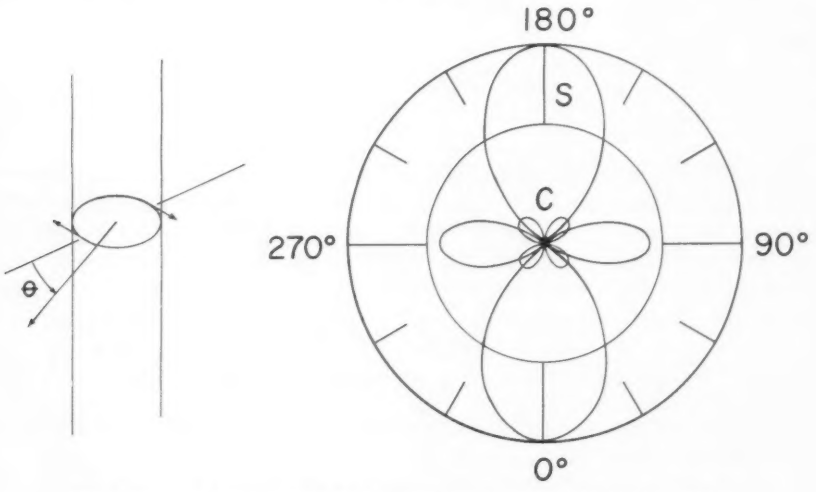

FIG. 3. Shear and compressional displacements due to tangential forces in cylinder.

compute the tangential displacement l_θ due to the application of a normal stress S perpendicular to the cylinder axis. At the cylinder wall, $N_\theta = S[1-2\cos 2\theta]$ and the other stresses are zero. Then

$$\frac{N_\theta}{Y} = \frac{S}{Y}[1 - 2\cos 2\theta] = \frac{1}{a}\frac{\partial l_\theta}{\partial \theta} + \frac{l_r}{a}.$$

From previous results $l_r/a = (1+2\cos 2\theta)S/Y$.

$$l_\theta = \int \frac{Sa}{Y}[1 - 2\cos 2\theta - 1 - 2\cos 2\theta]d\theta,$$

$$l_\theta = -2Sa \sin 2\theta / Y$$

is the tangential displacement due to a single normal stress S, to which should be added any translation or rotation of the body as a whole.

The disturbance from a radially-oriented point force carries a normal stress N oriented in the direction θ and a stress $\sigma N/(1-\sigma)$ perpendicular to θ and to the cylinder axis, plus a similar stress parallel to the cylinder which contributes nothing to the tangential displacements. Hence, for the arriving wave,

$$l_\theta = \frac{-2aN}{Y}\left[\sin 2\theta + \frac{\sigma}{(1-\sigma)}\sin 2\left(\theta + \frac{\pi}{2}\right)\right]$$

$$l_\theta = \frac{-2aN}{Y}\frac{(1-2\sigma)}{(1-\sigma)}\sin 2\theta = \frac{-2aN \sin 2\theta}{\rho V_s^2(1+\sigma)}. \tag{9}$$

For two forces oriented as shown, corresponding tangential displacements add. Overall translation cancels, and there is no rotation. Hence the desired sum of displacements is twice l_θ. Again taking N from Equation 2,

$$u_r = \frac{2a(1 - V_s^2/V_c^2)\sin 2\theta}{\pi r \rho V_c^3(3 - 4V_s^2/V_c^2)} f'(t - r/V_c). \tag{10}$$

This is the radial displacement at a distance r from a pair of forces acting tangentially at the ends of a diameter of a cylinder.

The radiation of shear waves can be obtained in a similar fashion. A shear wave from direction θ can be characterized by a tangential stress T and a bodily rotation of magnitude $T/2\mu$. The tangential displacement at the cylinder wall due to the shear stress T alone is obtained as the sum of displacements due to a normal stress of magnitude $-T$ at $(\theta+45°)$ and a normal stress of $+T$ at $(\theta-45°)$.

$$l_\theta = \frac{2Ta}{Y}[\sin 2(\theta + 45°) - \sin 2(\theta - 45°)] = \frac{4Ta}{Y}\cos 2\theta = \frac{2Ta}{\rho V_s^2(1+\sigma)}\cos 2\theta.$$

With addition of rotation term,

$$l_\theta = \frac{aT}{2\rho V_s^2}\left[1 + \frac{4}{(1+\sigma)}\cos 2\theta\right]. \tag{11}$$

Translation at the two points cancels, so the sum is twice l_θ above. Introducing T from equation 4,

$$u_\theta = \frac{a}{4\pi r\rho V_s^2}\left[1 + \frac{8(1 - V_s^2/V_c^2)}{(3 - 4V_s^2/V_c^2)}\cos 2\theta\right] f'(t - r/V_s). \tag{12}$$

This is the tangential displacement at a distance r from a pair of tangential forces on the wall of a cylindrical cavity.

Shear and compressional displacements for a pair of tangential forces are plotted in Figure 3, again taking V_s^2/V_c^2 to be $\frac{1}{3}$. Here the "reverse break" is quite pronounced, that is, for angles near 90°, the displacement is in the opposite direction from that which would be expected from the torque supplied by the pair of forces.

RADIATION FROM FINITE CYLINDER

The radiation of elastic waves due to the application of a transient pressure on the interior of a cylinder of finite length, which is of direct interest in seismic prospecting, was treated by Heelan (1953). Through a very complex derivation, he achieved results from which the expressions for long wavelengths and great distances from the source were extracted and discussed in detail. It is the purpose of this section to show that these expressions can be derived very simply by using the reciprocity relations.

There is symmetry about the cylinder axis, so the angular dependence on ϕ is sought. Assume that the interior of the cylindrical length, L, is divided into M small equal areas with a point force acting in each, radially on the cylinder wall. The average radial displacement around such a cylindrical length due to a compressional wave from a direction ϕ has been derived, White (1953).

$$\bar{l}_r = \frac{aN}{Y}\left[\frac{\sigma(1+\sigma) + (1 - \sigma - 2\sigma^2)\sin^2\phi}{(1-\sigma)}\right].$$

The desired sum is simply $M\bar{l}_r$. Again using equation 2,

$$u_r = \frac{aM}{4\pi r V_c Y}\left[\frac{\sigma(1+\sigma) + (1 - \sigma - 2\sigma^2)\sin^2\phi}{(1-\sigma)}\right] f'(t - r/V_c).$$

For direct comparison with Heelan's result, $f/(\pi a^2 L/M)$ is defined as a pressure p, and identities among elastic constants are used, leading to exactly his equation,

$$u_r = \frac{\pi a^2 L}{4\pi r\mu V_c}\left(1 - \frac{2V_s^2\cos^2\phi}{V_c^2}\right) p'(t - r/V_c).$$

Arrival of an SV wave from a direction ϕ produces an average radial displacement,

$$\bar{l}_r = -T \sin 2\phi/\mu.$$

Following the corresponding steps as for the compressional wave, Heelan's result is again duplicated,

$$u_s = \frac{\pi a^2 L}{4\pi r \mu V_s} \sin 2\phi \; p'(t - r/V_s).$$

This agreement with the low-frequency limit of Heelan's more refined derivation gives confidence in the reasoning being followed here, and reference to Heelan's article will emphasize the relative simplicity which has been achieved.

HOLE IN PLATE

It was felt that a direct comparison between calculation and experiment could be made most easily by means of two-dimensional seismic modelling. For this purpose, a crystal plug was mounted in a hole in a plastic plate so as to exert oppositely directed forces, as shown in Figure 4.

In order to compute the radiated displacements by reciprocity, one needs the expression for a single point force acting in the plane of the plate. Toward this end, equations (1) and (3) for sinusoidal time dependence can be integrated to give the shear and compressional waves in an infinite solid radiated by forces distributed along a line and acting perpendicular to the line (for instance, Rayleigh, 1894). As demonstrated by Oliver et al (1954), solutions in an infinite solid which have no component of motion along one axis are entirely equivalent to solutions for a plate, providing the speed of compressional waves in the plate, V_p, is substituted for the speed of compressional waves in the solid, V_c.

Hence, for a point force $Fe^{j\omega t}$ in a plate, the displacement at a distant point in line with the force is entirely radial, expressed by

$$U_R e^{j\omega t} = \frac{F\sqrt{\pi}\sqrt{V_p}}{2\pi\rho V_p^2\sqrt{2\omega r}} e^{-j\left(\frac{\omega r}{V_p} + \frac{\pi}{4}\right)} e^{j\omega t}.$$

The normal stress in the direction of propagation is,

$$Ne^{j\omega t} = \frac{-j\omega F\sqrt{\pi}}{2\pi\sqrt{V_p}\sqrt{2\omega r}} e^{-j\left(\frac{\omega r}{V_p} + \frac{\pi}{4}\right)} e^{j\omega t}.$$

The displacement at a point on a line perpendicular to the force is entirely tangential, given by

$$U_\theta e^{j\omega t} = \frac{F\sqrt{\pi}\sqrt{V_s}}{2\pi\rho V_s^2\sqrt{2\omega r}} e^{-j\left(\frac{\omega r}{V_s} + \frac{\pi}{4}\right)} e^{j\omega t}.$$

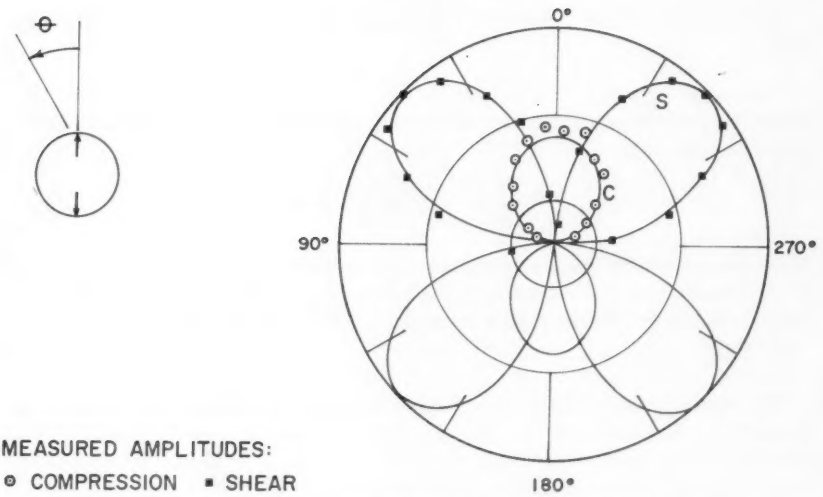

FIG. 4. Shear and compressional displacements due to radial forces on hole in plate.

The tangential stress accompanying this displacement is,

$$Te^{j\omega t} = \frac{-j\omega F\sqrt{\pi}}{2\pi\sqrt{V_s}\sqrt{2\omega r}}\, e^{-j}\left(\frac{\omega r}{V_s} + \frac{\pi}{4}\right) e^{j\omega t}.$$

Deriving the expression for compressional waves radiated by a pair of forces in a hole in a plate parallels the treatment of such a pair of forces in an infinite cylinder. The compressional wave arriving at the hole carries a normal stress N in the direction of travel and σN at right angles. The resulting displacement of a point on the hole relative to its center is,

$$l_r = \frac{aN}{Y}\left[1 + 2\cos 2\theta + \sigma - 2\sigma\cos 2\theta\right],$$

$$l_r = \frac{aN}{2\rho V_s^2}\left[1 + \frac{2(V_s/V_p)^2}{1 - (V_s/V_p)^2}\cos 2\theta\right],$$

where

$$\sigma = \left[1 - 2(V_s/V_p)^2\right].$$

Again, the desired sum of displacements, corresponding to two points on opposite ends of a hole diameter, is twice l_r. Hence the radial displacement due to a pair of oppositely directed forces in a hole in a plate is

$$U_r e^{j\omega t} = -\frac{aF}{2\rho V_s^2}\left(\frac{j\omega}{2\pi r V_p}\right)^{1/2}\left(1 + \frac{2(V_s/V_p)^2}{1-(V_s/V_p)^2}\cos 2\theta\right) e^{j\omega(t-r/V_p)}.$$

In similar fashion, the tangential displacement is found to be

$$U_\theta e^{j\omega t} = -\frac{aF}{\rho V_s^2}\left(\frac{j\omega}{2\pi r V_s}\right)^{1/2}\frac{\sin 2\theta}{[1-(V_s/V_p)^2]}\, e^{j\omega(t-r/V_s)}.$$

It is to be noted that U_r is a travelling compressional wave and U_θ a shear wave, each decreasing in amplitude as the square root of the distance. Each contains the term $(j\omega)^{1/2}$ which indicates that if the force is actually a transient pulse of a certain waveform, then the waveform of the displacement is different. However, the shear and compressional displacements have the same waveform, and hence their magnitudes can be compared.

With a plug of Rochelle salt contacting a half-inch diameter hole at two points, waves radiated into a quarter-inch plate of plexiglas were detected by means of a phonograph pick-up. Observed waveforms, with a dominant frequency of about 9 kc, are shown in Figure 5. Measured peak-to-peak amplitudes divided by a maximum shear amplitude are compared with calculations in Figure 4. Normalized to its maximum amplitude, the tangential function is simply sin 2θ. Dividing the radial displacement by the maximum shear displacement gives the expression

$$(V_s/V_p)^{1/2}[1-(V_s/V_p)^2 + 2(V_s/V_p)^2\cos 2\theta]/2,$$

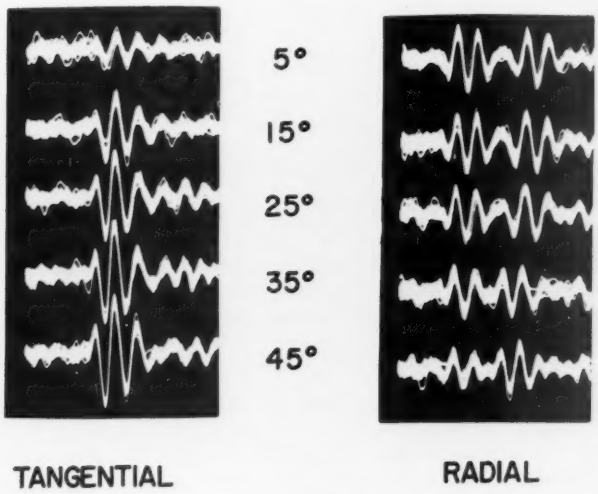

FIG. 5. Waveforms due to radial forces on hole in plate.

which is plotted as the compressional curve, using the measured value $V_s/V_p = 0.57$ for the plate. Agreement is considered satisfactory, as indicated by dependence on angle and ratio of compressional to shear amplitudes.

CONCLUSION

The very general reciprocity between forces and displacements can be used to simplify drastically the computation of the radiation of shear and compressional waves from localized sources.

LIST OF SYMBOLS

a = radius of cylinder (or hole)
f = transient force
F = force amplitude at frequency ω
l = displacement at hole or cylinder
L = length of finite cylinder
N = normal stress
p = transient pressure
r, θ, ϕ = spherical coordinates about source
R, S = normal stress
T = shear stress
u = transient particle displacement
U = displacement amplitude at ω
V_c = speed of compressional waves
V_p = speed of compressional waves in plate
V_s = speed of shear waves
Y = Young's modulus
μ = shear rigidity
ρ = density
σ = Poisson's ratio
ω = angular frequency

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GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 625–641, 2 FIGS.

THE METHOD OF GENERALIZED REFLECTION AND TRANSMISSION COEFFICIENTS*

T. W. SPENCER†

ABSTRACT

The objective of this work is to provide a method for predicting the *surface* response of a stratified half space to the radiation from a *localized* source when *neither the assumptions of the plane wave theory nor the assumptions of the normal mode theory are valid*. The earth model consists of a finite number of perfectly elastic, homogeneous, isotropic layers separated by interfaces which are plane and parallel to one another.

The method leads to an infinite series for the Laplace transform of the response function (displacement, velocity, stress, etc.) in a multi-interface system. Each term in the series describes *all* the energy which traverses a particular generalized ray path between the source and the receiver. The specification of the mode of propagation across each stratum (either as an irrotational wave or as an equivoluminal wave) and of the sequence in which the strata are traversed serve to define a generalized ray path. A prescription is given for constructing the integral representation for the disturbance which has traversed such a path directly from the integral representation for the source radiation. The method therefore obviates the necessity for solving a tedious boundary value problem. The time function associated with each term can be obtained by using Cagniard's method.

THE BASIC IDEA

Consider an elastic system which consists of two half spaces perfectly coupled together along a *plane* interface. Suppose that there is embedded in medium 1 a source of finite dimensions. If the source radiation is axially symmetric about some normal to the interface (say the z axis), then the energy which is reflected from and transmitted across the interface will also be axially symmetric about the z axis.

Our first step is to find general expressions for the scalar and vector potentials in an axially symmetric system. We then use these general expressions to represent the radiation field of the "most general" axially symmetric source. Using this source, we then solve the boundary value problem for a single interface between two half spaces. The solution yields integral representations for the reflected and transmitted waves. However, since both the reflected and transmitted waves are also axially symmetric about the z axis, the integral representations which describe these waves must have the same form as the integral representations for the radiation field of the source. It is then shown that the integral representations for the reflected and transmitted waves can be obtained directly from the integral representation for the radiation field of the source by following a certain prescription. The prescription utilizes "generalized reflection and transmission coefficients." These coefficients depend only on the velocities and densities in the two media adjacent to each interface. These quantities do

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not depend on the location of the source, the geometry of the source, or the location at which the response is determined (i.e., the detector).

Since we started with a perfectly general axially symmetric source, the prescription for constructing the integral representations for the reflected and transmitted waves is applicable to any type of axially symmetric source.

The next step is to note that if a second interface is introduced in such a way that it is parallel to the first interface, then it too will see an axially symmetric field which is either the field produced by the energy transmitted across the first interface or the sum of the fields produced by the energy reflected from the first interface and the direct energy from the source. In either case, the "effective" source as far as the second interface is concerned is axially symmetric—hence, the integral representations for the energy reflected and transmitted at the second interface can be derived from the integral representation for the "effective source" by again using the prescription. It is now evident that in a multi-interface system in which the interfaces are plane and parallel, the integral representations for the energy which is reflected and transmitted at each interface can be obtained by repeated use of the prescription.

In what follows, we go through the steps which lead to the prescription.

MATHEMATICAL PRELIMINARIES

Helmholtz's theorem (H. B. Phillips, 1948) states that any continuously varying vector field can be expressed as the sum of an irrotational and a solenoidal vector field. The displacement field in an elastic medium can therefore be represented in the form

$$\vec{D} = \nabla\phi + \nabla \times \vec{A} \tag{1}$$

where ϕ is the scalar displacement potential and $\vec{A}$ is the vector displacement potential.

The fractional change in volume of an elementary volume element is equal to the divergence of the vector displacement $(\nabla \cdot \vec{D})$. Since $\nabla \cdot (\nabla \times \vec{A}) = 0$, the part of the displacement field which is derived from the vector potential must be associated with equivoluminal waves. Waves of this type cause a rotation of the elementary volume element which is not accompanied by a change in volume.

The rotation of the elementary volume element is proportional to the curl of the vector displacement $(\nabla \times \vec{D})$. Since $\nabla \times (\nabla\phi) = 0$, the part of the displacement field which is derived from the scalar potential must be associated with irrotational waves. Waves of this type cause a change in volume which is not accompanied by a change in orientation.

In an unbounded, homogeneous, isotropic, perfectly elastic medium, these two wave types propagate independently of one another—that is, there is no transfer of energy from either wave type to the other. If the medium is *bounded* conversion can take place at the interfaces. The energy which is radiated away

from an interface after reflection or transmission cannot undergo further conversion unless it again interacts with the interface. If the energy is not radiated away from the interface (as in the case of interface waves), a continual interchange of energy between the two wave types must occur.

Throughout the subsequent discussion, we will restrict our attention to a geometry in which the vector displacement is axially symmetric about a vertical axis which is normal to the system of interfaces. In an axially symmetric geometry, the angular component of displacement (D_θ) vanishes, and neither the radial displacement (D_ρ) nor the vertical displacement (D_z) depends on the angular coordinate θ. Only the scalar potential and the θ component of the vector potential (A_θ) are required to determine the displacement field, and both are independent of θ. Equation 1 reduces to

$$D_\theta = 0, \qquad D_\rho = \frac{\partial \phi}{\partial \rho} - \frac{\partial A_\theta}{\partial z}, \qquad D_z = \frac{\partial \phi}{\partial z} + \frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho A_\theta). \tag{2}$$

The scalar potential and the θ component of the vector potential are solutions of the equations

$$\nabla^2 {}_i\phi = \frac{1}{V_i^2}\frac{\partial^2 {}_i\phi}{\partial t^2}, \qquad \nabla^2 {}_iA_\theta - \frac{{}_iA_\theta}{\rho^2} = \frac{1}{v_i^2}\frac{\partial^2 {}_iA_\theta}{\partial t^2}, \tag{3}$$

where

$$\nabla^2 = \frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial}{\partial \rho} + \frac{\partial^2}{\partial z^2},$$

V_i is the velocity of the irrotational body wave, v_i is the velocity of the equivoluminal body wave, and the subscript i refers to the ith stratum.

The Laplace transform of ${}_i\phi(t, \rho, z)$ is defined by the equation

$${}_i\bar{\phi}(s; \rho, z) = \int_0^\infty e^{-st}\, {}_i\phi(t; \rho, z)dt. \tag{4}$$

The Fourier-Bessel transform of order p of ${}_i\phi(t; \rho, z)$ is defined by the equation

$${}_i\Phi(t; q, z) = \int_0^\infty \rho\, {}_i\phi(t; \rho, z)J_p(\rho q)d\rho, \tag{5}$$

where J_p is the Bessel function of the first kind of order p.

Ordinary differential equations in z result from the successive application of the appropriate Fourier-Bessel and Laplace transforms to (3). The application of the Fourier-Bessel transform of order zero and the subsequent application of the Laplace transform to the equation for ${}_i\phi$ yield

$$\frac{d^2\, {}_i\bar{\Phi}(s; q, z)}{dz^2} - \left(q^2 + \frac{s^2}{V_i^2}\right){}_i\bar{\Phi}(s; q, z) = 0. \tag{6}$$

Effectively, we have replaced the differential operators with respect to ρ and t by the algebraic quantities q and s. An equation in ${}_i\overline{A}_\theta(s; q, z)$ which is in every respect identical to (6) except for the replacement of V_i by v_i can be obtained from the equation for ${}_iA_\theta$ by the successive application of the Fourier-Bessel transform of order one and the Laplace transform. The general solutions for the transformed functions are

$$ {}_i\bar{\Phi}(s; q, z) = E_i(s, q)e^{-(q^2+s^2/V_i^2)^{1/2}z} + F_i(s, q)e^{(q^2+s^2/V_i^2)^{1/2}z}, \tag{7} $$

$$ {}_i\overline{A}_\theta(s; q, z) = G_i(s, q)e^{-(q^2+s^2/v_i^2)^{1/2}z} + H_i(s, q)e^{(q^2+s^2/v_i^2)^{1/2}z}. \tag{8} $$

The application of the appropriate Fourier-Bessel inversion formulas* to (7) and (8) yields

$$ {}_i\bar{\Phi}(s; \rho, z) = \int_0^\infty qE_i(s, q)J_0(q\rho)e^{-\alpha_i z}dq + \int_0^\infty qF_i(s, q)J_0(q\rho)e^{\alpha_i z}dq, \tag{9} $$

$$ {}_i\overline{A}_\theta(s; \rho, z) = \int_0^\infty qG_i(s, q)J_1(q\rho)e^{-\beta_i z}dq + \int_0^\infty qH_i(s, q)J_1(q\rho)e^{\beta_i z}dq, \tag{10} $$

where $\alpha_i=(q^2+s^2/V_i^2)^{1/2}$ and $\beta_i=(q^2+s^2/v_i^2)^{1/2}$. Equations 9 and 10 are completely general expressions for the potentials in an axially symmetric system.

The functions E_i, F_i, G_i, and H_i depend not only on the Laplace transform variable (s) and the integration variable but also on the parameters which specify the source geometry (radius, height, etc.), on quantities which specify the position of the source relative to the origin ($\rho=z=0$), and on the type of coupling existing between the source and the medium. Consider a perfectly general axially symmetric source having a finite vertical extension e (along the z axis). Let h be the minimum vertical distance between the plane $z=0$ and the surface of the source (see Figure 1). The medium in which the source is embedded will be designated as medium 1. If medium 1 is unbounded, the response at sufficiently large distances in both the positive and negative z directions must become vanishingly small due to geometrical spreading. This implies that in region 1 only the second integral in equations (9) and (10) is a permissible solution. The first integral in equations (9) and (10) contains either the factor $e^{-\alpha_1 z}$ or the factor $e^{-\beta_1 z}$ (the subscript one is used because (9) and (10) determine the radiation field in medium 1). Both of these factors are unbounded as z approaches minus infinity if the cuts in the plane of the integration variable, q, are made in such a way that the real parts of α_1 and β_1 are positive on the positive real q axis. We conclude that in region 1, the functions E_1 and G_1 must vanish. In like manner, it can be shown that in region 3 only the first integral in equations (9) and (10) is a permissible solution. In region 2, both integrals are permissible solutions.

It will prove convenient to write the functions F_1 and H_1 in the form:

* The function ${}_i\bar{\Phi}(s; \rho, z)$ is given in terms of its Fourier-Bessel transform by the equation

$$ {}_i\bar{\Phi}(s; \rho, z) = \int_0^\infty q\,{}_i\bar{\Phi}(s; q, z)J_p(q\rho)dq. $$

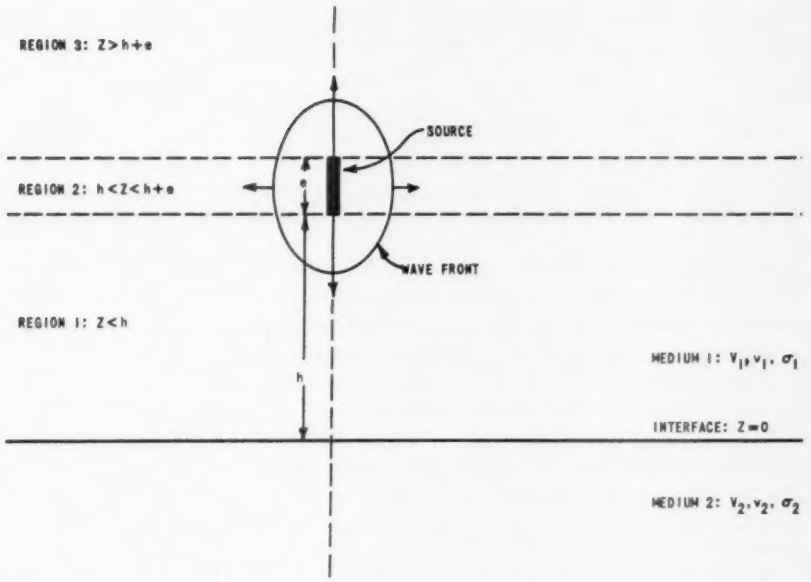


FIG. 1. The radiation field of a localized source can be divided into three regions. In regions 1 and 3 the amplitude of the response must go to zero as $|Z|$ goes to infinity. It is this fact which dictates which of the terms in equations (9) and (10) must be used to describe the radiation field in each of the three regions.

$F_1 = F'e^{-\alpha_1 h}$, $H_1 = H'e^{-\beta_1 h}$. The Laplace transform for the potentials in region 1 can then be written in the form

$$_{\text{source}}\bar{\Phi}(s; \rho, z) = \int_0^\infty qF'(s, q)J_0(q\rho)e^{-\alpha_1(h-z)}dq, \qquad z < h, \tag{11}$$

$$_{\text{source}}\bar{A}_\theta(s; \rho, z) = \int_0^\infty qH'(s, q)J_1(q\rho)e^{-\beta_1(h-z)}dq, \qquad z < h. \tag{12}$$

In the absence of the interface, the properties of the radiation field at every point in the region below the source ($z<h$) can be derived from (11) and (12).

In the subsequent discussion, we will focus attention on the vertical component of the particle velocity (we could just as well have chosen the rotation, dilatation, or a stress component). The Laplace transform of the vertical component of displacement can be obtained by applying (2) to (11) and (12). The Laplace transform of the vertical component of the particle velocity is then obtained by attaching a multiplicative factor, s, to the result. Next we introduce the transformation $q = su$. If we regard s as a positive real variable, this transformation amounts to nothing more than a change of scale. The Laplace trans-

form of the vertical component of the particle velocity in region 1 can, as a result of this sequence of operations, be written as follows:

$$
\begin{aligned}
{}_{\text{source}}\bar{v}_z(s;\rho,z) = &\int_0^\infty uJ_0(su\rho)F''(s,u)e^{-sa_1(h-z)}du \\
&+\int_0^\infty uJ_0(su\rho)H''(s,u)e^{-sb_1(h-z)}du, \qquad z<h,
\end{aligned} \tag{13}
$$

where $F''=s^4a_1F'$, $H''=s^4uH'$, $a_1=(u^2+1/V_1^2)^{1/2}$, and $b_1=(u^2+1/v_1^2)^{1/2}$. The first term is derived from the scalar potential—hence, it describes the motion produced by irrotational waves. The second term is derived from the vector potential —hence, it describes the motion produced by equivoluminal waves.

The procedure for solving the boundary value problem for a single plane interface is well known and will not be carried out here. We assume that the interface is coincident with the plane $z=0$ and that the stress and displacement components are continuous at the interface (perfect coupling). The medium below the interface will be designated as medium 2. The radiation field of the source is given by (11) and (12). The transform of the total response in medium 1 is given by

$$
\begin{aligned}
{}_1\bar{v}_z(s;\rho,z) = &\overset{P_1}{\int_0^\infty} uJ_0(su\rho)F''(s,u)e^{-sa_1(h-z)}du + \overset{S_1}{\int_0^\infty} uJ_0(su\rho)H''(s,u)e^{-sb_1(h-z)}du \\
&+\overset{P_1P_1}{\int_0^\infty} uJ_0(su\rho)F''(s,u)R^z_{P_1P_1}(u)e^{-sa_1(h+z)}du \\
&+\overset{P_1S_1}{\int_0^\infty} uJ_0(su\rho)F''(s,u)R^z_{P_1S_1}(u)e^{-s(a_1h+b_1z)}du \\
&+\overset{S_1S_1}{\int_0^\infty} uJ_0(su\rho)H''(s,u)R^z_{S_1S_1}(u)e^{-sb_1(h+z)}du \\
&+\overset{S_1P_1}{\int_0^\infty} uJ_0(su\rho)H''(s,u)R^z_{S_1P_1}(u)e^{-s(b_1h+a_1z)}du.
\end{aligned} \tag{14}
$$

The response in medium 2 is given by

$$
\begin{aligned}
{}_2\bar{v}_z(s;\rho,z) = {} & \overset{P_1P_2}{\int_0^\infty} uJ_0(su\rho)F''(s,u)T^z_{P_1P_2}(u)e^{-s(a_1h-a_2z)}du \\
& + \overset{P_1S_2}{\int_0^\infty} uJ_0(su\rho)F''(s,u)T^z_{P_1S_2}(u)e^{-s(a_1h-b_2z)}du \\
& + \overset{S_1S_2}{\int_0^\infty} uJ_0(su\rho)H''(s,u)T^z_{S_1S_2}(u)e^{-s(b_1h-b_2z)}du \\
& + \overset{S_1P_2}{\int_0^\infty} uJ_0(su\rho)H''(s,u)T^z_{S_1P_2}(u)e^{-s(b_1h-a_2z)}du.
\end{aligned}
\tag{15}
$$

The functions $R^z_{P_1P_1}(u)$, $R^z_{P_1S_1}(u)$, $R^z_{S_1S_1}(u)$, and $R^z_{S_1P_1}(u)$ will be referred to as generalized reflection coefficients. The explicit form for these functions is given below:

$$
R^z_{P_1P_1} = Q_1/D_1,\ R^z_{P_1S_1} = -u^2Q_2/D_1,\ R^z_{S_1S_1} = -R_1/D_1,\ R^z_{S_1P_1} = a_1b_2Q_2/D_1; \tag{16}
$$

where

$$
\begin{aligned}
D_1 = {} & u^2\left(u^2+\frac{B_1}{v_1^2}+\frac{B_2}{v_2^2}\right)^2 + u^2a_1b_1a_2b_2 - a_1b_1\left(u^2+\frac{B_2}{v_2^2}\right)^2 \\
& - a_2b_2\left(u^2+\frac{B_1}{v_1^2}\right)^2 + \frac{B_1B_2}{v_1^2v_2^2}(a_1b_2+a_2b_1),
\end{aligned}
\tag{17}
$$

$$
B_1 = (1/2)(1/(1-\sigma_2v_2^2/\sigma_1v_1^2)),
$$

$$
B_2 = (1/2)(\sigma_2v_2^2/\sigma_1v_1^2)/((\sigma_2v_2^2/\sigma_1v_1^2)-1);
$$

$$
\begin{aligned}
Q_1 = {} & u^2\left(u^2+\frac{B_1}{v_1^2}+\frac{B_2}{v_2^2}\right)^2 - u^2a_1b_1a_2b_2 + a_1b_1\left(u^2+\frac{B_2}{v_2^2}\right)^2 \\
& - a_2b_2\left(u^2+\frac{B_1}{v_1^2}\right)^2 - \frac{B_1B_2}{v_1^2v_2^2}(a_1b_2-a_2b_1);
\end{aligned}
\tag{18}
$$

$$
Q_2 = 2\left\{\left(u^2+\frac{B_1}{v_1^2}+\frac{B_2}{v_2^2}\right)\left(u^2+\frac{B_2}{v_2^2}\right) - a_2b_2\left(u^2+\frac{B_1}{v_1^2}\right)\right\}; \tag{19}
$$

$$R_1 = u^2\left(u^2 + \frac{B_1}{v_1^2} + \frac{B_2}{v_2^2}\right)^2 - u^2 a_1 b_1 a_2 b_2 + a_1 b_1\left(u^2 + \frac{B_2}{v_2^2}\right)^2 - a_2 b_2\left(u^2 + \frac{B_1}{v_1^2}\right)^2 + \frac{B_1 B_2}{v_1^2 v_2^2}(a_1 b_2 - a_2 b_1). \tag{20}$$

The quantities σ_1 and σ_2 are the densities in media 1 and 2 respectively.

The functions $T^{\varepsilon}_{P_1P_2}(u)$, $T^{\varepsilon}_{P_1S_2}(u)$, $T^{\varepsilon}_{S_1P_2}(u)$, and $T^{\varepsilon}_{S_1S_2}(u)$ will be referred to as generalized transmission coefficients. These functions have the form:

$$T^{\varepsilon}_{P_1P_2} = a_2 Q_3/D_1,\ T^{\varepsilon}_{P_1S_2} = u^2 Q_4/D_1,\ T^{\varepsilon}_{S_1P_2} = a_2 b_1 R_3/D_1,\ T^{\varepsilon}_{S_1S_2} = b_1 R_4/D_1; \tag{21}$$

where

$$Q_3 = 2\frac{B_1}{v_1^2}\left(b_1\left(u^2 + \frac{B_2}{v_2^2}\right) - b_2\left(u^2 + \frac{B_1}{v_1^2}\right)\right); \tag{22}$$

$$Q_4 = 2\frac{B_1}{v_1^2}\left(\left(u^2 + \frac{B_1}{v_1^2} + \frac{B_2}{v_2^2}\right) - a_2 b_1\right); \tag{23}$$

$$R_3 = 2\frac{B_1}{v_1^2}\left(\left(u^2 + \frac{B_1}{v_1^2} + \frac{B_2}{v_2^2}\right) - a_1 b_2\right); \tag{24}$$

$$R_4 = 2\frac{B_1}{v_1^2}\left(a_1\left(u^2 + \frac{B_2}{v_2^2}\right) - a_2\left(u^2 + \frac{B_1}{v_1^2}\right)\right). \tag{25}$$

Note that the subscript 1 refers to the medium which is traversed by the waves just prior to impinging upon the interface. The generalized reflection and transmission coefficients are functions of the integration variable u, the density ratio σ_2/σ_1, and the irrotational and equivoluminal velocities in the two media adjacent to the interface. It is also important to note that these coefficients contain none of the geometry of the problem. They do not depend on the coordinates which specify the position of the source or detector or the geometrical parameters which are required to specify the source shape. The reason for the appellation "generalized reflection and transmission coefficients" will become more apparent as we proceed.

THE PRESCRIPTION

From a study of the structure of the integrands in equations (14) and (15), it is possible to write down a prescription which permits the construction of integral representations for the reflected and transmitted waves directly from the integral representation for the radiation field of the source. Since we have not restricted ourselves to a particular source geometry (spherical, vertical line segment, plane, etc.) the results so obtained are applicable to any radiation field which is axially symmetric about a normal to the interface.

Consider first the response in medium 1 (equation 14). The radiation field of the source is described by the first two terms. The remaining terms describe the radiation field associated with the reflected energy (i.e., if the interface were absent, these terms would be absent). The third and sixth terms are derived from the scalar potential—hence, they describe the irrotational component of motion in the reflected field. The third term would be absent if the source radiation consisted entirely of equivoluminal waves (for then F'' would be identically zero). We conclude that the third term describes the irrotational component of motion produced by incident irrotational waves which are reflected as irrotational waves. The sixth term describes the irrotational component of motion produced by incident equivoluminal waves which are converted upon reflection to irrotational waves. The fourth and fifth terms are derived from the vector potential—hence, they describe the equivoluminal component of motion in the reflected field. The fourth term describes the equivoluminal component of motion produced by incident irrotational waves which are converted upon reflection to equivoluminal waves. The fifth term describes the equivoluminal component of motion produced by incident equivoluminal waves which are reflected as equivoluminal waves.

Clearly we need a short-hand notation for the individual terms in equations (14) and (15). For this reason, we introduce the concept of a *generalized ray path. To define a generalized ray path in a multi-interface system, we must specify the mode of propagation across the region between each pair of adjacent interfaces (either as irrotational waves or as equivoluminal waves) and the sequence in which the strata are traversed.* With this definition in mind, we label the first term in (14) P_1. This label indicates that the first term describes the response produced by the energy which traverses the region between the plane $z=h$ and the detector in the form of irrotational waves. Similarly, we label the sixth term S_1P_1. This label indicates that the sixth term describes the response produced by energy which traverses the region between the plane $z=h$ and the interface in the form of equivoluminal waves, which is converted to waves of irrotational type upon reflection, and subsequently traverses the region between the interface and the detector in the form of irrotational waves. Clearly each term in equation 14 describes all the energy which traverses the generalized path indicated by the label. For example, S_1P_1 describes all the energy which is incident in the form of equivoluminal waves which is subsequently radiated away from the interface in the form of irrotational waves. This includes not only the reflected body wave which follows the least time reflection path and the head waves which travel along the interface with the speeds of irrotational and equivoluminal waves in medium 2, but also waves which follow non-least-time paths. The only requirement for a wave to fall into the category S_1P_1 is that it be incident as an equivoluminal wave and subsequently be reflected as an irrotational wave. If this condition is satisfied by a wave, then its effect is included in the term S_1P_1 and the actual path of propagation is immaterial.

The physical significance of each of the terms which determine the response in medium 2 can be ascertained in a like manner from the steps leading to equation (15). The second and third terms are derived from the vector potential—hence, they describe the equivoluminal component of motion in medium 2. The second term would be absent if the incident radiation consisted entirely of equivoluminal waves. Therefore, the second term describes the effect produced by incident irrotational waves which are transmitted as equivoluminal waves. The third term describes the effect produced by equivoluminal waves which are transmitted as equivoluminal waves. The first and fourth terms are derived from the scalar potential—hence, they describe the irrotational component of motion in medium 2. The first term would be absent if the incident radiation consisted entirely of equivoluminal waves. Therefore, the first term describes the effect produced by incident irrotational waves which are transmitted as irrotational waves. The fourth term describes the effect produced by incident equivoluminal waves which are transmitted as irrotational waves. The labels above each term indicate the associated generalized ray path.

Next consider the result of allowing z to approach zero through positive values in equation (14) and through negative values in equation (15). The response in medium 1 "at" the interface is given by

$$
\begin{aligned}
{}_1\bar{v}_z(s;\rho,0) = {} & \overline{P_1} \int_0^\infty uJ_0(su\rho)F''(s,u)e^{-sa_1h}du + \overline{S_1} \int_0^\infty uJ_0(su\rho)H''(s,u)e^{-sb_1h}du \\
& + \overline{P_1P_1} \int_0^\infty uJ_0(su\rho)F''(s,u)R^z_{P_1P_1}(u)e^{-sa_1h}du \\
& + \overline{P_1S_1} \int_0^\infty uJ_0(su\rho)F''(s,u)R^z_{P_1S_1}(u)e^{-sa_1h}du \\
& + \overline{S_1S_1} \int_0^\infty uJ_0(su\rho)H''(s,u)R^z_{S_1S_1}(u)e^{-sb_1h}du \\
& + \overline{S_1P_1} \int_0^\infty uJ_0(su\rho)H''(s,u)R^z_{S_1P_1}(u)e^{-sb_1h}du.
\end{aligned}
\tag{26}
$$

The response "at" the interface in medium 2 is given by

$$
{}_2\bar{v}_z(s,\rho,0) = \overline{P_1P_2} \int_0^\infty uJ_0(su\rho)F''(s,u)T^z_{P_1P_2}(u)e^{-sa_1h}du
$$

$$
\begin{aligned}
&\qquad\qquad P_1S_2 \\
&+\int_0^\infty uJ_0(su\rho)F''(s,u)T^z_{P_1S_2}(u)e^{-sa_1h}\,du \\
&\qquad\qquad S_1S_2 \\
&+\int_0^\infty uJ_0(su\rho)H''(s,u)T^z_{S_1S_2}(u)e^{-sb_1h}\,du \\
&\qquad\qquad S_1P_2 \\
&+\int_0^\infty uJ_0(su\rho)H''(s,u)T^z_{S_1P_2}(u)e^{-sb_1h}\,du
\end{aligned}
\tag{27}
$$

At the interface the term which describes the incident irrotational waves (P_1) differs from the term which describes the incident irrotational waves which are reflected as irrotational waves (P_1P_1) by the factor $R^z_{P_1P_1}(u)$. *The important point is that at the interface the integrands in the expressions for P_1 and P_1P_1 differ by a factor which does not in any way depend on the source position or source geometry. Analogous remarks hold for the other terms in equations (26) and (27).* This means that the terms which describe the reflected and transmitted waves can be constructed directly from the terms which describe the incident waves in a manner which is exactly analogous to that used in plane wave theory. It is for this reason that I have designated $R^z_{P_1P_1}, \cdots, T^z_{P_1P_2}, \cdots$, etc. as generalized reflection and transmission coefficients. They are "generalized" because they do not depend on any of the factors required to specify the position or shape of the source—they are therefore independent of the radius of curvature of the incident wave-fronts at the points of intersection of these wave-fronts with the interface.

It is important not to confuse the generalized coefficients with the plane wave coefficients. In plane wave theory, the expressions for the reflected and transmitted waves are obtained by multiplying the expression for the incident wave by the plane wave reflection and transmission coefficients. In curved wave-front theory, the generalized coefficients do not multiply the source term itself but multiply instead the integrand in the integral representation for the source term.

It should be emphasized that the generalized reflection and transmission coefficients which we have been considering apply only to the vertical component of the particle velocity (or displacement). Generalized reflection and transmission coefficients can also be found for the radial component of the particle velocity, the stress components, the dilatation, and the rotation. In each case, the quantity of interest (i.e., normal stress, dilatation, etc.) in the reflected and transmitted radiation can be derived from the integral representation for that quantity in the incident wave by using the generalized reflection and transmission coefficients appropriate for that quantity.

It is interesting to note that the ordinary plane wave reflection and transmission coefficients for the vertical component of the particle velocity in an incident irrotational wave result upon substituting $-i \sin\theta/V_1$ for u in the expressions

for $R^{z}_{P_1P_1}$, $R^{z}_{P_1S_1}$, $T^{z}_{P_1P_2}$, and $T^{z}_{P_1S_2}$. The ordinary plane wave reflection and transmission coefficients for the vertical component of the particle velocity in an incident equivoluminal wave result upon substituting $-i \sin \theta/v_1$ for u in the expressions for $R^{z}_{S_1S_1}$, $R^{z}_{S_1P_1}$, $T^{z}_{S_1S_2}$, and $T^{z}_{S_1P_2}$. In each case θ is to be interpreted as the angle which the normal to the plane wave-front makes with the normal to the interface.

The form of the generalized reflection and transmission coefficients depends only on the type of coupling which is assumed to exist at the interface. In deriving the expressions given in equations (16) through (25) perfect coupling was assumed (i.e., no relative motion at the interface). For perfect coupling to exist, the normal and tangential components of both the stress and the displacement must be continuous at the interface. Different forms of the generalized reflection and transmission coefficients are obtained at the interface between a liquid and a solid (where the tangential displacement need not be continuous) and at a lubricated crack between two solids (where neither the tangential stress nor the tangential displacement need be continuous).

We have seen that the response "at" the interface can be constructed directly from the integral representation for the source radiation at the interface by using the generalized reflection and transmission coefficients in the same manner as the ordinary plane wave reflection and transmission coefficients. To obtain the response elsewhere (as given by equations (14) and (15)) we need a prescription for generating the exponentials. A study of equations (14) and (15) reveals that if the disturbance traverses the region between two planes separated by a distance d as an irrotational wave, the integral representation for that disturbance contains the exponential $e^{-Sda}(a=(u^2+1/V^2)^{1/2})$, where V is the speed of irrotational waves in the region bounded by the two planes. Similarly, if the disturbance traverses the same region as an equivoluminal wave the integral representation contains the exponential $e^{-Sdb}(b=(u^2+1/v^2)^{1/2})$, where v is the speed of equivoluminal waves in the region bounded by the two planes. This means that the proper form for the exponential can be determined directly from the specification of the generalized path. For example, the label S_1P_1 indicates that the associated term describes the total effect produced by all waves which traverse the region between the source ($z=h$) and the interface as equivoluminal waves, which are converted upon reflection to waves of irrotational type, and traverse the region between the interface and the detector as irrotational waves. The path between the source and the interface contributes the factor e^{-Sb_1h}; the path between the interface and the detector contributes the factor e^{-Sa_1z}.

SYSTEMS CONSISTING OF MORE THAN ONE INTERFACE

In a multi-interface system the energy which is reflected and transmitted at each interface will be axially symmetric provided that the interfaces are plane and parallel and the source radiation is axially symmetric about a normal to the system of interfaces. It follows that the prescription can be used to construct

directly from the integral representation for the source integral representations for the waves which are reflected and transmitted at each interface. Repeated use of the prescription yields the integral representation for the disturbance which has traversed any generalized ray path.

To illustrate the use of the prescription in a system consisting of two interfaces, we construct the integral representation for $P_1P_2S_2$. The upper interface coincides with the plane $z=0$ and the lower interface coincides with the plane $z=-d$ (Figure 2). At a height h above the upper interface, we put a point source which radiates spherically symmetric irrotational waves. The integral representation for the Laplace transform of the vertical component of the particle velocity in the radiation field of the point source can be written in the form (Dix, C. H., 1954)

$$_{\text{source}}\bar{v}_z(s;\rho,z) = s\bar{\kappa}(s)\int_0^\infty uJ_0(su\rho)e^{-sa_1(h-z)}du, \qquad z<h, \tag{28}$$

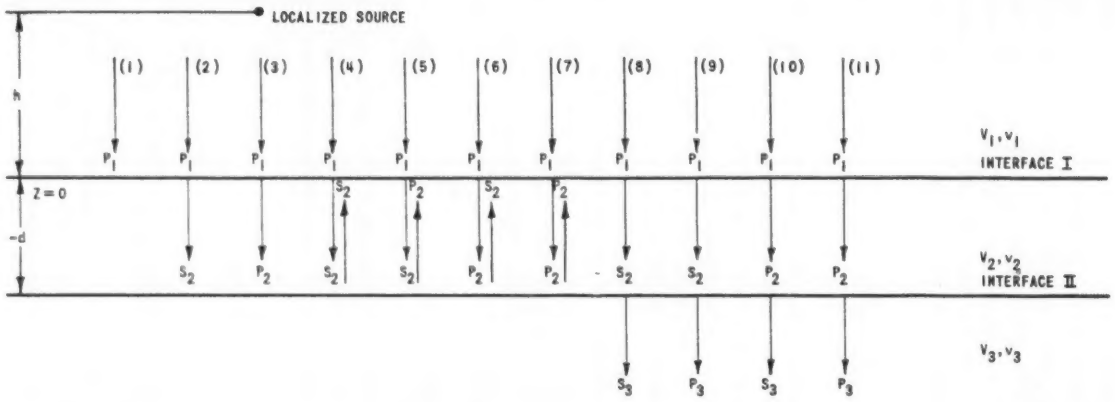
$\bar{\kappa}(s)$ is the Laplace transform of the function which describes the time variation of the particle velocity in the direct wave. The label $P_1P_2S_2$ indicates that the incident irrotational waves are transmitted across the upper interface without change of type. The appropriate transmission coefficient is $T^z_{P_1P_2}(u)$. At the lower interface the incident irrotational waves are converted to equivoluminal waves upon reflection. The appropriate reflection coefficient is $R^z_{P_2S_2}(u)$. The disturbance traverses the region between the source and the upper interface as an irrotational wave, between the upper and lower interfaces as an irrotational wave, and between the lower interface and the detector as an equivoluminal wave. The proper form of the exponential is $e^{-sha_1}e^{-sda_2}e^{-s(d+z)b_2}$. Note that $d+z$ is the distance between the lower interface and the plane in which the detector is located (z is negative). The integral representation for $P_1P_2S_2$ is,

$$_{P_1P_2S_2}\bar{v}_z(s;\rho,z) = s\bar{\kappa}(s)\int_0^\infty uJ_0(su\rho)T^z_{P_1P_2}(u)R^z_{P_2S_2}(u)e^{-s(a_1h+a_2d+b_2(d+z))}du. \tag{29}$$

To check this result let us take the integral representation for the transmitted field produced in medium 2 by the point source as a new source and solve the boundary value problem for a single interface at $z=-d$. The integral representation for the transmitted field is,

$$_2\bar{v}_z(s;\rho,z) = s\bar{\kappa}(s)\left\{\int_0^\infty uJ_0(su\rho)T^z_{P_1P_2}(u)e^{-s(a_1h-a_2z)}du + \int_0^\infty uJ_0(su\rho)T^s_{P_1S_2}(u)e^{-s(a_1h-b_2z)}du\right\}. \tag{30}$$

For a point compressional source, this result can be obtained directly from (15) by setting $F''=s\bar{\kappa}(s)$ and $H''=0$. The first term describes the irrotational component of motion; the second term describes the equivoluminal component of



(1) $I\, e^{-\alpha_1(h-z)}$	P_1	DIRECT COMPRESSIONAL	(7) $T_{P_1P_2}R_{P_2P_2}e^{-(\alpha_1 h+\alpha_2(2d+z))}$ COMPRESSIONAL REFLECTION (II)
(2) $T_{P_1S_2}e^{-(\alpha_1 h-\beta_2 z)}$	P_1S_2	TRANSMITTED SHEAR (I)	(8) $T_{P_1S_2}T_{S_2S_3}e^{-(\alpha_1 h+\beta_2 d-\beta_3(d+z))}$ SHEAR TRANSMISSION (II)
(3) $T_{P_1P_2}e^{-(\alpha_1 h-\alpha_2 z)}$	P_1P_2	TRANSMITTED COMPRESSIONAL (I)	(9) $T_{P_1S_2}T_{S_2P_3}e^{-(\alpha_1 h+\beta_2 d-\alpha_3(d+z))}$ SHEAR TO COMPRESSIONAL CONVERSION UPON TRANSMISSION (II)
(4) $T_{P_1S_2}R_{S_2S_2}e^{-(\alpha_1 h+\beta_2(2d+z))}$	$P_1S_2S_2$	SHEAR REFLECTION (II)	(10) $T_{P_1P_2}T_{P_2S_3}e^{-(\alpha_1 h+\alpha_2 d-\beta_3(d+z))}$ COMPRESSIONAL TO SHEAR CONVERSION UPON TRANSMISSION (II)
(5) $T_{P_1S_2}R_{S_2P_2}e^{-(\alpha_1 h+\beta_2 d+\alpha_2(d+z))}$	$P_1S_2P_2$	SHEAR TO COMPRESSIONAL CONVERSION UPON REFLECTION (II)	(11) $T_{P_1P_2}T_{P_2P_3}e^{-(\alpha_1 h+\alpha_2 d-\alpha_3(d+z))}$ COMPRESSIONAL TRANSMISSION (II)
(6) $T_{P_1P_2}R_{P_2S_2}e^{-(\alpha_1 h+\alpha_2 d+\beta_2(d+z))}$	$P_1P_2S_2$	COMPRESSIONAL TO SHEAR CONVERSION UPON REFLECTION (II)	

FIG. 2. The symbol at the tip of the arrow indicates the mode of propagation between two adjacent horizontal planes. The arrow indicates whether the vertical component of the energy flux is downward or upward. Each number refers to a particular generalized ray path. The associated term describes all the energy which traverses that generalized ray path. The arrows are not to be confused with least time paths.

motion. The complete expression for the radiation field produced by the reflection of the direct waves (given by equation 30) at the lower interface is

$$\begin{aligned}\bar{v}_z(s;\rho,z) = s\bar{k}(s)\Big\{&\int_0^\infty uJ_0(su\rho)T^z_{P_1P_2}(u)R^z_{P_2P_2}(u)e^{-s(a_1h+a_2(2d+z))}du\\ &+\int_0^\infty uJ_0(su\rho)T^z_{P_1P_2}(u)R^z_{P_2S_2}(u)e^{-s(a_1h+a_2d+b_2(d+z))}du\\ &+\int_0^\infty uJ_0(su\rho)T^z_{P_1S_2}(u)R^z_{S_2P_2}(u)e^{-s(a_1h+b_2d+a_2(d+h))}du\\ &+\int_0^\infty uJ_0(su\rho)T^z_{P_1S_2}(u)R^z_{S_2S_2}(u)e^{-s(a_1h+b_2(2d+z))}du\Big\}, \quad -d<z<0.\end{aligned} \tag{31}$$

The second term is identical with the result obtained using the prescription. It can be readily shown that the first, third, and fourth terms describe the velocity response produced by disturbances which have traversed the generalized ray paths $P_1P_2P_2$, $P_1S_2P_2$, and $P_1S_2S_2$ respectively.

The use of the prescription in a system consisting of two or more enterfaces leads to an infinite series representation for the total response. Each term in the series is the Laplace transform of a time function which describes the particle velocity response produced by energy which has traversed a specific generalized ray path. Cagniard's method can be used to derive the time function associated with each term if the functions which contain the information on the source geometry and position (i.e., the functions $F''(s, u)$ and $H''(s, u)$, in equation 13) can be written in the form

$$\sum_{i=1}^{k} m_i(s)n_i(u)e^{-sp_i(u)}.$$

Associated with each generalized ray path there is a least time path and an origin time before which there is no contribution to the total response. It follows that only a finite number of terms are required to describe the total response over a finite time interval. Application of Cagniard's method yields integral expressions for the time functions associated with each term. These integrals can be evaluated numerically on a high speed digital computer such as the 704. The cost of obtaining the response over the time interval of interest becomes prohibitive when the number of terms which contribute to the total response during that time interval is large. It is this fact which limits the usefulness of the method at the present time.

Under certain conditions it may be possible to approximate the response associated with energy transmission along a generalized ray path by the use of plane wave theory corrected for geometrical spreading. It can be shown (Spencer, T. W., 1956) that if the *least time path* associated with a particular generalized

ray path is a reflection path (not a refraction path) the exact response function can be expressed as the sum of a "plane wave" term and a "correction" term.

Apart from the factor which takes into account the change in amplitude produced by geometrical spreading, the plane wave term can be obtained directly from plane wave theory. The correction term contains those effects which are due to the finite curvature of the wave-front. The question naturally arises concerning the relative importance of these two terms. In the study of the irrotational part of the impulse response of a single interface excited by a spherically symmetric irrotational wave diverging from a point source certain characteristics of the correction term have been noted which have a bearing on this problem. For example, if the angle of incidence of the wave which follows the least time reflection path is held fixed, the Fourier spectrum of the correction term is displaced toward lower frequencies as the radius of curvature of the direct wave is increased. The time variation in the plane wave term does not depend on the radius of curvature—hence, the shape of the Fourier spectrum of the plane wave term is insensitive to changes in the radius of curvature.

The amount by which a particular frequency component in the spectrum of the correction term is displaced is directly proportional to the change in the radius of curvature and to the frequency. This result is valid regardless of whether the least time path is a reflection path or a refraction path. If the least time path is a reflection path (i.e.—if the detector lies inside the critical angle) the Fourier amplitude spectrum of the correction term goes to zero as the frequency approaches infinity. It follows that if the radius of curvature is large enough the correction term will contain very little energy in the pass band of the recording system relative to that of the plane wave term. The problem of what is large enough is under investigation. Whether or not it is practical to use the method of generalized reflection and transmission coefficients in a particular problem will depend on the number of terms required to predict those characteristics of the response which are not described by plane wave theory corrected for geometrical spreading.

SUMMARY

A mathematical symbolism is introduced which has the effect of transforming a two-dimensional problem into a one-dimensional one. This is accomplished by working with the Fourier-Bessel and Laplace transforms of the response function rather than with the response function itself. In effect these transformations reduce the problem to that of finding the response of a layered half space to vertically traveling plane waves. To use the method all that is required is an integral representation for the Laplace transform of the axially symmetric radiation field of the source. The formal solution for the response associated with energy transmission along any generalized ray path can then be obtained directly from the integral representation for the source by using the generalized coefficients in place of the plane wave coefficients. The beauty of the method lies in the fact

that it is possible to go directly to the solution without first solving the boundary value problem.

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GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 642-648, 1 FIG.

SCATTERING OF ELASTIC WAVES BY SMALL INHOMOGENEITIES*

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ABSTRACT

Rayleigh scattering theory is extended to determine the perturbation on an arbitrarily prescribed elastic wave field produced by small inhomogeneities in an otherwise homogeneous, isotropic medium. The general result is applied to the specific problems of the scattering of both plane P- and S-waves. It is found that a change in compressibility acts at a distance as a simple source and a change in density as a dipole, as in the acoustical problem, while a change in shear modulus contributes both simple-source and quadrapole fields.

INTRODUCTION

We consider here the scattering of elastic waves by small inhomogeneities in an isotropic medium (see (1) below for a more precise definition of *small*). The corresponding acoustical (longitudinal waves only) and optical (transverse waves only) problems were solved long ago by Rayleigh (see *Theory of Sound*, §§296 and 375), while the mathematical framework for the solution of the elastic problem goes back to Stokes (1849). Rayleigh (1871) pointed out that, on dimensional grounds, the scattered field at distances large compared with the wave length must be proportional to $V\kappa^2 r^{-1}$, where V denotes the volume of the small inhomogeneity, r the distance to the point of observation, and κ the wave number (inversely proportional to the wave length).

Rayleigh's scattering law applies also to acoustical scattering by a small obstacle of infinite density and stiffness (e.g., a rigid, immobile sphere; see *Theory of Sound*, §334) and to elastic scattering by a rigid obstacle of finite density (Wolf, 1945). Elastic scattering by a rigid obstacle of infinite density appears to constitute a singular exception, however, in that the constraints required to fix the rigid body render the scattered field proportional to $A\kappa r^{-1}$, where A denotes the area of the obstacle (Yamakawa, 1956; see also Knopoff, 1959).

A second, general characteristic of Rayleigh scattering is that a deviation in compressibility acts as a simple source, yielding a spherically symmetric, scattered wave, whereas a deviation in density acts as a dipole, yielding a scattered wave proportional to the cosine of the angle between the direction of incidence (of a plane wave) and the direction of observation. We anticipate that P-wave scattering also will partake of these qualities and that, in addition, deviations in shear modulus will lead to a quadrapole radiation (in analogy with radiation from faults).

FORMAL SOLUTION

We consider an isotropic elastic medium that is homogeneous except in a small domain V, where it is slightly inhomogeneous Let λ_0, μ_0 and ρ_0 denote the

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Lamé constants and the density outside of V; then by *slightly inhomogeneous*, we mean that

$$\lambda = \lambda_0 + \lambda_1, \cdots, \quad |\lambda_1/\lambda_0| \ll 1, \cdots \quad . \tag{1}$$

Similarly, letting $\boldsymbol{q}^{(0)}(\boldsymbol{r})$ denote a displacement that satisfies the equations of motion for $\lambda \equiv \lambda_0, \cdots$, we may define the complete displacement as

$$\boldsymbol{q}(\boldsymbol{r}) = \boldsymbol{q}^{(0)}(\boldsymbol{r}) + \boldsymbol{q}^{(1)}(\boldsymbol{r}), \quad |\boldsymbol{q}^{(1)}| \ll |\boldsymbol{q}^{(0)}|, \tag{2}$$

where $\boldsymbol{q}^{(1)}$ denotes the perturbation displacement excited by $\boldsymbol{q}^{(0)}$ in consequence of the inhomogeneity in V. We shall assume that $\boldsymbol{q}^{(0)}$, and therefore $\boldsymbol{q}^{(1)}$ also, exhibits the harmonic time dependence $\exp(i\omega t)$ with the usual convention with respect to complex amplitudes. Given $\boldsymbol{q}^{(0)}$, we then seek $\boldsymbol{q}^{(1)}$.

We first observe that the total force per unit volume is given by

$$f_i = \rho\omega^2 q_i + \sigma_{ij,j}, \tag{3}$$

where $\rho\omega^2 q_i$ denotes the inertial force associated with the acceleration $-\omega^2 q_i$ and

$$\sigma_{ij} = \lambda\delta_{ij}q_{k,k} + \mu(q_{i,j} + q_{j,i}), \tag{4}$$

denotes the Cartesian stress tensor. Single subscripts denote components of a vector (e.g., q_i is a Cartesian component of $\boldsymbol{q}$), double subscripts components of the stress tensor and subscripts following a comma, differentiation with respect to the corresponding Cartesian coordinate; repeated subscripts imply summation according to the usual convention, and δ_{ij} is the Kronecker delta. We next observe that, from the viewpoint of an observer outside of V, $\boldsymbol{q}^{(1)}$ may be regarded as having been generated by the perturbation force obtained by replacing ρ, λ and μ in (3) and (4) by ρ_1, λ_1 and μ_1; accordingly, we may determine $\boldsymbol{q}^{(1)}(\boldsymbol{r})$ as a superposition of disturbances generated by the infinitesimal forces $\boldsymbol{f}(\boldsymbol{r}')dV(\boldsymbol{r}')$ integrated through V.

The disturbance produced by a time-dependent force acting at a point in an elastic medium was determined originally by Stokes (1849; see also Love, 1944, §212 and Rayleigh, 1945, §378) and is given by

$$4\pi\rho_0\omega^2\boldsymbol{q} = -\nabla\nabla\cdot\boldsymbol{G}\left(t - \frac{r}{\alpha}\right) + \nabla\times\nabla\times\boldsymbol{G}\left(t - \frac{r}{\beta}\right),$$

$$\boldsymbol{G}(t) = \frac{1}{r}\boldsymbol{F}(t), \tag{5a}$$

in vector notation or

$$4\pi\rho_0\omega^2 q_i = \left[G_j\left(t - \frac{r}{\beta}\right) - G_j\left(t - \frac{r}{\alpha}\right)\right]_{,ij} - \left[G_i\left(t - \frac{r}{\beta}\right)\right]_{,jj}, \tag{5b}$$

in tensor notation; here $\boldsymbol{F}$ denotes the force, r the distance from its point of application to the point of observation, and α and β the speeds of dilatational and shear waves—viz.,

$$\alpha^2 = (\lambda_0 + 2\mu_0)/\rho_0, \qquad \beta^2 = \mu_0/\rho_0. \tag{6a, b}$$

It then follows from the principle of superposition that we may calculate the disturbance produced by a distribution of force $\boldsymbol{f}(\boldsymbol{r}, t)$ by evaluating $\boldsymbol{G}_i$ according to

$$\boldsymbol{G} = \iiint \boldsymbol{f}_i\left(\boldsymbol{r}', t - \frac{R}{\alpha}\right)\frac{dV(\boldsymbol{r}')}{R}, \tag{7}$$

where

$$R = |\boldsymbol{r} - \boldsymbol{r}'| = [(x_i - x_i')(x_i - x_i')]^{1/2}. \tag{8}$$

Introducing the time dependence $\exp(i\omega t)$, suppressing the explicit appearance of t, and abbreviating $dV(\boldsymbol{r}')$ by dV', we may replace (7) by

$$\boldsymbol{G}(\boldsymbol{r}) = \iiint \boldsymbol{f}(\boldsymbol{r}')e^{-i\kappa_\alpha R}\frac{dV'}{R}, \tag{9}$$

where

$$\kappa_\alpha = \omega/\alpha. \tag{10}$$

The volume integral in (9), and subsequently, is over V, and we may replace α by β as required.

Substituting (3) in (9) with $\rho = \rho_1$ etc., integrating the term in $\sigma_{ij,j}$ by parts, noting that

$$\frac{\partial}{\partial x_i'}\frac{e^{-i\kappa R}}{R} = -\frac{\partial}{\partial x_i}\frac{e^{-i\kappa R}}{R}, \tag{11}$$

and invoking the fact (from the definition of V) that λ_1 and μ_1 vanish on the surface bounding V, we obtain

$$G_i^{(1)} = \iiint \left\{\rho_1\omega^2 q_i + [\lambda_1\delta_{ij}q_{k,k} + \mu_1(q_{i,j} + q_{j,i})]\left(\frac{\partial}{\partial x_j}\right)\right\}\frac{e^{-i\kappa R}}{R}dV' \tag{12}$$

where κ denotes either κ_α or κ_β, and the argument of q_i is $\boldsymbol{r}'$. We remark that the substitution of (12) in (5b) yields an exact but implicit result, which becomes approximate but explicit if $\boldsymbol{q}$ is approximated by $\boldsymbol{q}^{(0)}$ in the determination of $\boldsymbol{G}$. The superscript (1) on G_i implies that its substitution in (5b) yields only $q_i^{(1)}$.

FAR FIELD APPROXIMATION

We now invoke the approximation

$$\kappa r \gg 1 \gg \kappa r', \tag{13}$$

thereby implying that the dimensions of V are small compared with the wave length and that the distance from V to the point of observation is large compared with the wave length. We then may approximate R by r in (12) and approximate

the derivatives with respect to x_i according to (Note that $r_{,i}=x_i/r$ are the direction cosines of r and that $r_{,i}r_{,i}=1$).

$$\left(\frac{\partial}{\partial x_i}\right)\left(\frac{e^{-i\kappa R}}{R}\right) \doteq -i\kappa r_{,i}\frac{e^{-i\kappa r}}{r} \tag{14}$$

in virtue of $\kappa r \gg 1$, while $\kappa r' \ll 1$ permits the approximation

$$\iiint \rho_1(r')q_i(r')dV' \doteq q_i^{(0)}\iiint \rho_1 dV', \tag{15}$$

and similarly for the other terms in (12). These approximations lead to

$$G_i^{(1)} = \frac{e^{-i\kappa r}}{r}\left\{P_1\omega^2 q_i - i\kappa[\lambda_1\delta_{ij}q_{k,k} + \mu_1(q_{i,j}+q_{j,i})]r_{,j}\right\} \tag{16}$$

in place of (12), while substituting (16) in (5b) yields

$$4\pi\rho_0\omega^2 q_i^{(1)} = \kappa_\alpha^2\frac{e^{-i\kappa_\alpha r}}{r}r_{,i}\left\{P_1\omega^2 r_{,j}q_j - i\kappa_\alpha[\Lambda_1 q_{k,k} + M_1(q_{j,k}+q_{k,j})r_{,j}r_{,k}]\right\}$$

$$+\kappa_\beta^2\frac{e^{-i\kappa_\beta r}}{r}(\delta_{ij}-r_{,i}r_{,j})[P_1\omega^2 q_j - i\kappa_\beta M_1(q_{j,k}+q_{k,j})r_{,k}], \tag{17}$$

where

$$P_1, \Lambda_1, M_1 = \iiint (\rho_1, \lambda_1, \mu_1)dV', \tag{18}$$

and q_i and its derivatives may be replaced by $q_i^{(0)}$ and its derivatives evaluated at the origin. Further investigation suggests that the approximations may be optimized by choosing the origin at the centroid of the distributions ρ_1, λ_1 and μ_1 (assuming that these distributions have a common centroid).

We specifically remark that the approximations (16) and (17) do not assume ρ_1, λ_1 and μ_1 to be uniform throughout V; indeed, any attempt to invoke such an assumption would have rendered the analysis far more difficult in consequence of the implicit discontinuities (infinite gradients) at the boundaries of V. This statement notwithstanding, the final approximations are independent of the details of the distributions, and we may (if convenient) take ρ_1, λ_1 and μ_1 to be uniform in evaluating the integrals of (18).

SCATTERING OF PLANE P-WAVE

We consider the plane P-wave

$$q_i^{(0)} = n_i e^{-i\kappa_\alpha n_j x_j} \tag{19}$$

to be incident on V; n_i are the components of the wave front normal, and the

amplitude of $\boldsymbol{q}^{(0)}$ is unity. Substituting (19) in (17) and noting that

$$\overset{(0)}{q}_i = n_i, \qquad \overset{(0)}{q}_{k,k} = -i\kappa_\alpha, \qquad \overset{(0)}{q}_{i,j} + \overset{(0)}{q}_{j,i} = -2i\kappa_\alpha n_i n_j \text{ at } r = 0, \tag{20}$$

we obtain

$$4\pi\rho_0 \overset{(0)}{\boldsymbol{q}} = \kappa_\alpha^2 \frac{e^{-i\kappa_\alpha r}}{r} \boldsymbol{r}_1 \left\{ P_1(\boldsymbol{n}\cdot\boldsymbol{r}_1) - \frac{1}{\alpha^2}\left[\Lambda_1 + 2M_1(\boldsymbol{n}\cdot\boldsymbol{r}_1)^2\right]\right\}$$
$$+ \kappa_\beta^2 \frac{e^{-i\kappa_\beta r}}{r}\left[\boldsymbol{n} - (\boldsymbol{n}\cdot\boldsymbol{r}_1)\boldsymbol{r}_1\right]\left[P_1 - \frac{2M_1}{\alpha\beta}(\boldsymbol{n}\cdot\boldsymbol{r}_1)\right], \tag{21}$$

where

$$\boldsymbol{n}\cdot\boldsymbol{r}_1 = n_j r_{,j} = \cos\theta, \tag{22}$$

$\boldsymbol{r}_1$ being the unit radial vector and θ the polar angle between $\boldsymbol{r}$ and $\boldsymbol{n}$. If we also introduce the unit vector $\boldsymbol{\theta}_1$ (see Figure 1), we may rewrite (21) as

$$4\pi\rho_0 \overset{(1)}{\boldsymbol{q}} = \kappa_\alpha^2 \frac{e^{-i\kappa_\alpha r}}{r} \boldsymbol{r}_1\left[-\left(\frac{\Lambda_1 + M_1}{\alpha^2}\right) + P_1\cos\theta - \frac{M_1}{\alpha^2}\cos 2\theta\right]$$
$$+ \kappa_\beta^2 \frac{e^{-i\kappa_\beta r}}{r}\boldsymbol{\theta}_1\left(-P_1\sin\theta + \frac{M_1}{\alpha\beta}\sin 2\theta\right). \tag{23}$$

Generalizing Rayleigh's observations for the acoustical problem (*Theory of Sound*, §296), we remark that the scattered wave of (23) comprises a simple

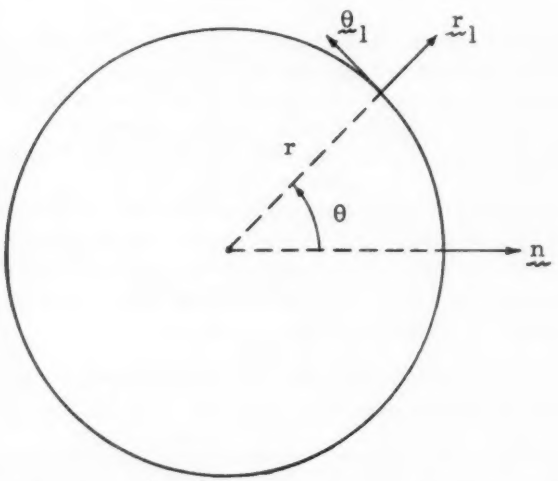

FIG. 1. The Spherical Polar Coordinates for the Scattered Wave of Equation (23).

source of strength proportional to Λ_1+M_1, a dipole of strength proportional to P_1, and a quadrapole of strength proportional to M_1. If $\mu\equiv 0$ we must discard the S-wave terms in (23), which then reduces to Rayleigh's result.

SCATTERING OF A PLANE S-WAVE

We may specify a plane S-wave by

$$q_i^{(0)} = m_i e^{-i\kappa_\beta n_j x_j}, \qquad m_j n_j = 0, \tag{24}$$

where m_i are the direction cosines of the transverse displacement of unit amplitude. We then obtain

$$q_i^{(0)} = m_i, \quad q_{k,k}^{(0)} = 0, \quad q_{i,j}^{(0)} + q_{j,i}^{(0)} = -i\kappa_\beta(m_i n_j + m_j n_i) \text{ at } r = 0, \tag{25}$$

and

$$\begin{aligned} 4\pi\rho_0 \boldsymbol{q} = {} & \kappa_\alpha^2 \frac{e^{-i\kappa_\alpha r}}{r} (\boldsymbol{m}\cdot\boldsymbol{r}_1)\boldsymbol{r}_1\left[P_1 - \frac{M_1}{\alpha\beta}(\boldsymbol{n}\cdot\boldsymbol{r}_1)\right] \\ & + \kappa_\beta^2 \frac{e^{-i\kappa_\beta r}}{r}\left\{[\boldsymbol{m} - (\boldsymbol{m}\cdot\boldsymbol{r}_1)\boldsymbol{r}_1]\left[P_1 - \frac{M_1}{\beta^2}(\boldsymbol{n}\cdot\boldsymbol{r}_1)\right]\right. \\ & \left. - [\boldsymbol{n} - (\boldsymbol{n}\cdot\boldsymbol{r}_1)\boldsymbol{r}_1]\frac{M_1}{\beta^2}(\boldsymbol{m}\cdot\boldsymbol{r}_1)\right\}. \end{aligned} \tag{26}$$

Introducing θ_m and θ_n according to

$$\boldsymbol{m}\cdot\boldsymbol{r}_1 = \cos\theta_m, \qquad \boldsymbol{n}\cdot\boldsymbol{r}_1 = \cos\theta_n, \tag{27}$$

and unit vectors $\boldsymbol{\theta}_m$ and $\boldsymbol{\theta}_n$, with $\boldsymbol{\theta}_n$ directed in an $\boldsymbol{r}_1$, $\boldsymbol{n}$ plane as in Figure 1 and similarly for $\boldsymbol{\theta}_m$ in an $\boldsymbol{r}_1$, $\boldsymbol{m}$ plane, we may transform (26) to

$$\begin{aligned} 4\pi\rho_0 \boldsymbol{q}^{(1)} = {} & \kappa_\alpha^2 \frac{e^{-i\kappa_\alpha r}}{r}\boldsymbol{r}_1\left[P_1\cos\theta_m - \frac{M_1}{\alpha\beta}\cos\theta_m\cos\theta_n\right] \\ & + \kappa_\beta^2 \frac{e^{-i\kappa_\beta r}}{r}\left\{\boldsymbol{\theta}_m\left[-P_1\sin\theta_m + \frac{M_1}{\beta^2}\sin\theta_m\cos\theta_n\right]\right. \\ & \left. + \boldsymbol{\theta}_n\frac{M_1}{\beta^2}\cos\theta_m\sin\theta_n\right\}. \end{aligned} \tag{28}$$

We again may interpret the scattered wave in terms of a dipole field proportional to P_1 and a quadrapole field proportional to M_1. There is, however, no simple source field in consequence of the absence of dilation in the incident wave. If the medium is assumed to be incompressible we may discard the P-wave terms in (28), which then reduces to Rayleigh's result (1871) for the optical problem (based on an elastic aether); see also *Theory of Sound* §375 for the special case of density variations only.

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GEOPHYSICS, VOL. XXV, NO. 3, (JUNE, 1960), PP. 649–658, 1 FIG.

ON THE ELECTROMAGNETIC RESPONSE OF A CONDUCTING SPHERE TO A DIPOLE FIELD*

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ABSTRACT

The electromagnetic coupling between an electric and a magnetic dipole in the presence of a spherical ore body is discussed in the present paper. It is shown that both electric and magnetic modes must be considered even though all dimensions are small compared to the wave length. The results have application to a geophysical prospecting scheme where the exciting fields are set up by a straight insulating wire grounded at its end points and the secondary fields are detected by an ungrounded closed wire loop.

INTRODUCTION

Scattering of an electromagnetic wave by a spherical and homogeneous obstacle is a subject which has been investigated many times. The complete solution for plane wave incidence was published by Debye and Mie over 50 years ago. Much of the more recent work has been concerned with the problem of finding alternate forms of the Debye-Mie solution which are more convergent for large spheres. An excellent account of this early work is given in a treatise by Stratton (1941).

For most physical applications the assumption of plane wave incidence was satisfactory. In considering the diffraction of radio waves by the spherical bulge of the earth, G. N. Watson (1918) represented the transmitting antenna by a vertical electric dipole. The form of the solution obtained by Watson was a series of residues of poles in the complex plane highly convergent for large spheres. The accurate evaluation of the poles in the residue series was undertaken by Van der Pol and Bremmer (1937–39) who also made a large number of important theoretical extensions. Marion C. Gray (1939) further extended the theory to the case of excitation by a vertical magnetic dipole.

Solutions for the electromagnetic response of a sphere to a general dipolar field have only appeared in the literature quite recently (March 1953, Wait 1953). Some of this work has been motivated by application in geophysical prospecting for massive type ore bodies. As a rough approximation, the ore body is represented by a homogeneous sphere of arbitrary conductivity and magnetic permeability. The exciting field is usually set up by a coil or wire loop carrying an alternating current at a frequency in the range 200 to 2000 cps—or thereabouts. The secondary field of the ore body is then detected by a receiving coil or loop which may be oriented in various manners in order to take advantage of local conditions. In some cases, one or both of the coils may be in a drill hole. With such

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schemes it is usually permissible to regard the transmitting loop as a magnetic dipole. Furthermore, all significant dimensions of the problem are small compared to the wave length in the medium external to the spherical ore body. The expected response as measured by the receiving loop may then be obtained by solving a boundary problem whose solution is facilitated since the external magnetic fields are derivable from a single scalar (magnetic) potential. This may be described as a quasi-static solution since solutions of the Helmholtz (wave) equation required for the interior of the sphere are matched to solutions of Laplace's equation at the spherical boundary. This approach, of course, may also be used for other geometries such as for an oscillating magnetic dipole in the presence of horizontal slabs, conducting cylinders, or prolate and oblate spheroids. Unfortunately, a serious complication arises in the case of the spheroids (Wait, 1960). While the solution interior to the spheroid may be expanded in terms of radial and angular functions, in analogy to the Bessel and Legendre functions in spherical geometry, the boundary conditions couple all modes to one another. This coupling disappears when the spheroid is perfectly conducting, or at the other extreme when the wave length within the spheroid is very large.

The significant point concerning these quasi-static solutions is that only the induced magnetic dipole and multipoles need be considered. Conversely, if the excitation was by an electric dipole and the resulting electric fields in the external medium were of interest, it is only necessary to consider the induced electric dipole and multipoles. At least this is true in the quasi-static regime wherein the wave length external to the sphere is very large. Such a physical situation occurs in geophysical prospecting when the current is injected into the ground by an insulated wire which is grounded at its end points. The received field is measured by the voltage induced at the terminals of a similar wire also grounded at its end points. This is the basis of the so-called "resistivity method." While, strictly speaking, it is only valid for direct current, the concept still holds for alternating current if the wave length in the external media (i.e. the ground or barren rock) is large compared to the maximum distances between the electrodes.

The question now arises: what is the nature of the low frequency response of the sphere when the excitation is by an electric dipole and the resulting magnetic fields are measured? At first thought, one might expect only the induced electric dipoles and multipoles to be important since the conducting sphere primarily modifies the current flow in the medium. This answer, however, is inadequate as may be seen by taking the source to be the magnetic dipole and considering the resulting electric fields. Then one might think that only the induced magnetic dipole or multipoles are important. To reconcile these two equivalent situations it is thus necessary to consider the possibility of both induced electric and magnetic type dipoles and multipoles. This is true even though the dimensions of the sphere and distances between the source dipole and observer are all small compared to the external wave length. For this situation one must abandon

the usual quasi-static solution and return to the general electromagnetic problem of a sphere in an arbitrary dipole field.

THEORETICAL DEVELOPMENT

The spherical body has a radius a and possesses homogeneous electric properties denoted σ, ϵ, μ. The medium external to the sphere is assumed to be infinite in extent and homogeneous with electric properties σ_0, ϵ_0, μ_0. For a conventional spherical polar co-ordinate system (r, θ, ϕ) centered at the center of the sphere, the electric field components E_r, E_θ, E_ϕ and the magnetic field components H_r, H_θ, H_ϕ may be expressed in terms of the two H_ϕ scalar Debye functions denoted π^1, π^2 as follows

$$
\begin{aligned}
H_r^1 &= \left(k^2 + \frac{\partial^2}{\partial r^2}\right)(r\pi^1) \\
H_\theta^1 &= \frac{1}{r}\,\frac{\partial^2}{\partial r \partial \theta}\,(r\pi^1) \\
H_\phi^1 &= \frac{1}{r\sin\theta}\,\frac{\partial^2}{\partial r \partial \phi}\,(r\pi^1) \\
E_r^1 &= 0 \\
E_\theta^1 &= \frac{-i\mu\omega}{r\sin\theta}\,\frac{\partial(r\pi^1)}{\partial \phi} \\
E_\phi^1 &= \frac{i\mu\omega}{r}\,\frac{\partial(r\pi^1)}{\partial \theta},
\end{aligned}
\tag{1a}
$$

$$
\begin{aligned}
H_r^2 &= 0 \\
H_\theta^2 &= \frac{\sigma + i\epsilon\omega}{r\sin\theta}\,\frac{\partial}{\partial \phi}\,(r\pi^2) \\
H_\phi^2 &= \frac{-(\sigma + i\epsilon\omega)}{r}\,\frac{\partial}{\partial \theta}\,(r\pi^2) \\
E_r^2 &= \left(k^2 + \frac{\partial^2}{\partial r^2}\right)(r\pi^2) \\
E_\theta^2 &= \frac{1}{r}\,\frac{\partial^2}{\partial r \partial \theta}\,(r\pi^2) \\
E_\phi^2 &= \frac{1}{r\sin\theta}\,\frac{\partial^2(r\pi^2)}{\partial r \partial \phi}\,.
\end{aligned}
\tag{1b}
$$

The superscript 1 or 2 over the field components are to indicate that the

field component is derived from either π^1 or π^2, respectively. The first set is called H or magnetic modes and the second set is called E or electric modes. The functions π^1 and π^2 satisfy the scalar wave equation

$$(\nabla^2 + k^2)\begin{matrix}\pi^1 \\ \pi^2\end{matrix} = 0, \quad \text{where} \quad k^2 = \left(\epsilon - i\frac{\sigma}{\omega}\right)\mu\omega^2. \tag{2}$$

Solutions are of the form†

$$r^{-1}\begin{matrix}\hat{J}_n(kr) \\ \mathrm{P}_n^m(\cos\theta) \\ \hat{H}_n(kr)\end{matrix}\qquad\begin{matrix}\cos m\phi \\ \\ \sin m\phi,\end{matrix}$$

where

$$\hat{J}_n(kr) = \left(\frac{\pi k_0 r}{2}\right)^{1/2} \hat{J}_{n+1/2}(kr) \tag{3a}$$

$$\hat{H}_n(kr) = \left(\frac{\pi k_0 r}{2}\right)^{1/2} \hat{H}^{(2)}_{n+1/2}(kr) \tag{3b}$$

in terms of the usual cylindrical Bessel functions $J_{n+1/2}$ and $H^{(2)}_{n+1/2}$. $P_n^m(\cos\theta)$ is the associated Legendre Polynomial.

The source is now taken to be an electric dipole located at $r = b$ on the polar axis or at (o, o, b) in terms of a Cartesian co-ordinate system. Without loss of generality the dipole is contained in the plane $\phi = 0$ or the $x-z$ plane. With such an arrangement the primary field can be broken into two parts due to the x and z components of the dipole moments. These are denoted p_x and p_z respectively. In terms of the elemental length ds and the current I in the dipole

$$P_x = Ids \sin\psi$$

and

$$p_z = Ids \cos\psi,$$

where ψ is the angle which the dipole subtends with the z axis. The situation is illustrated in Figure 1. The primary field can then be derived from a Hertz vector $\overrightarrow{\Pi}^p$ which has only an x and a z component.

Actually it is simpler to consider the response of the sphere to the two dipole components separately. These will be referred to as the tangential dipole (i.e. p_x) and the radial dipole (i.e. p_z).

For the tangential dipole

$$\Pi_{px} = \frac{p_x}{4\pi}\,\frac{e^{-ik_0R}}{R}, \tag{4}$$

† Of course, outside the sphere σ, ϵ, μ and k in equations (1) to (3) are to be replaced by σ_0, ϵ_0, μ_0 and k_0, respectively.

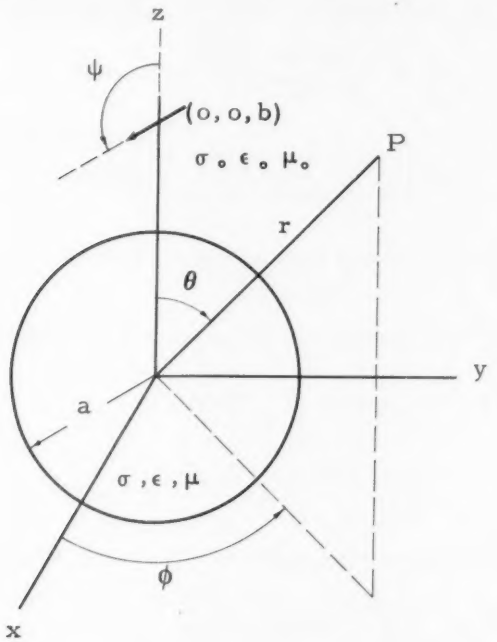

FIG. 1. Conducting sphere with electric dipole in its vicinity.

where

$$k_0^2 = \left(\epsilon_0 - \frac{i\sigma_0}{\omega}\right)\mu_0\omega^2$$

and

$$R = [b^2 + r^2 - 2br\cos\theta]^{1/2}.$$

Using the addition theorem (Watson, 1918)

$$\frac{e^{-ik_0R}}{R} = \sum_{n=0}^{\infty} d_n \frac{J_n(k_0r)}{r} P_n(\cos\theta) \qquad \text{for} \quad r < b, \qquad (5)$$

where

$$d_n = -i(2n+1)\hat{H}_n(k_0b)/k_0b,$$

it is then not difficult to show that the primary field may be derived from

$$\overset{1}{\pi}_p = \frac{p_x \sin\phi}{4\pi} \sum_{n=1}^{\infty} \alpha_n \frac{J_n(k_0r)}{r} P_n^1(\cos\theta) \qquad (6)$$

and

$$\pi_p^2 = \frac{p_x \cos\phi}{4\pi} \sum_{n=1}^{\infty} \beta_n \frac{\hat{J}_n(k_0 r)}{r} P_n^1(\cos\theta), \tag{7}$$

where

$$\alpha_n = \frac{-i(\sigma_0 + i\epsilon_0\omega)(2n+1)}{n(n+1)k_0 b} \hat{H}_n(k_0 b)$$

and

$$\beta_n = \frac{-(2n+1)\hat{H}_n'(k_0 b)}{n(n+1)b}.$$

The secondary field resulting from the presence of the sphere must be of the form

$$\pi_s^1 = \frac{p_x \sin\phi}{4\pi} \sum_{n=1}^{\infty} a_n^1 \frac{\hat{H}_n(k_0 r)}{r} P_n^1(\cos\theta) \tag{8a}$$

$$\pi_s^2 = \frac{p_x \cos\phi}{4\pi} \sum_{n=1}^{\infty} a_n^2 \frac{\hat{H}_n(k_0 r)}{r} P_n^1(\cos\theta), \tag{8b}$$

where a_n^1 and a_n^2 are undetermined coefficients. The field inside the sphere ($r<a$) has the form

$$\pi^1 = \frac{p_x \sin\phi}{4\pi} \sum_{n=1}^{\infty} b_n' \frac{\hat{J}_n(kr)}{r} P_n^1(\cos\theta) \tag{9a}$$

and

$$\pi^2 = \frac{p_x \cos\phi}{4\pi} \sum_{n=1}^{\infty} b_n^2 \frac{\hat{J}_n(kr)}{r} P_n^1(\cos\theta). \tag{9b}$$

By matching tangential field components in the usual way, the coefficients $a_n^{1,2}$ and $b_n^{1,2}$ may be expressed in terms of the known coefficients α_n and β_n. In particular,

$$\frac{a_n^1}{\alpha_n} = -\frac{\mu_0 \dfrac{(ka)\hat{J}_n'(ka)}{\hat{J}_n(ka)} - \mu \dfrac{(k_0 a)J_n'(k_0 a)}{\hat{J}_n(k_0 a)}}{\mu_0 \dfrac{(ka)J_n'(ka)}{\hat{J}_n(ka)} - \mu \dfrac{(k_0 a)\hat{H}_n'(k_0 a)}{\hat{H}_n(k_0 a)}} \cdot \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)}, \tag{10a}$$

$$\frac{a_n^2}{\beta_n} = -\frac{\dfrac{(\sigma_0 + i\epsilon_0\omega)(ka)J_n'(ka)}{\hat{J}_n(ka)} - \dfrac{(\sigma + i\epsilon\omega)(k_0 a)\hat{J}_n'(k_0 a)}{\hat{J}'(k_0 a)}}{\dfrac{(\sigma_0 + i\epsilon_0\omega)ka\hat{J}_n'(ka)}{\hat{J}_n(ka)} - \dfrac{(\sigma + i\epsilon\omega)(k_0 a)\hat{H}_n'(k_0 a)}{\hat{H}_n(k_0 a)}} \cdot \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)}. \tag{10b}$$

In the case of the radial dipole, the primary field is readily derived from

$$\Pi_{pz} = \frac{p_z}{4\pi} \frac{e^{-ik_0R}}{R}, \tag{11}$$

which is equivalent to $\pi_p^1 = 0$

$$\pi_p^2 = \frac{p_z}{4\pi b} \sum_{n=0}^{\infty} d_n \frac{\hat{J}_n(k_0 r)}{r} P_n(\cos\theta) \tag{12}$$

for $r < b$. The secondary field is then easily shown to be derived from

$$\begin{aligned} \pi_s^1 &= 0 \\ \pi_s^2 &= \frac{p_z}{4\pi b} \sum_{n=0}^{\infty} e_n \frac{\hat{H}_n(k_0 r)}{r} P_n(\cos\theta), \end{aligned} \tag{13}$$

where

$$e_n = d_n \cdot \frac{a_n^2}{\beta_n}. \tag{14}$$

The ratio a_n^2/β_n is given above.

Approximations are now made exploiting the fact that the sphere is electrically small (i.e. $k_0 a \ll 1$) and other dimensions are also small compared to the external wave length (i.e. $k_0 r$ and $k_0 b \ll 1$). Using the small argument approximations for Bessel functions it is not at all difficult to show that

$$\frac{a_n^1}{\alpha_n} \cong -\left[\frac{\mu_0 \alpha \dfrac{\hat{I}_n'(\alpha)}{\hat{I}_n(\alpha)} - \mu(n+1)}{\mu_0 \alpha \dfrac{\hat{I}_n'(\alpha)}{\hat{I}_n(\alpha)} + \mu n}\right] \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)}, \tag{15a}$$

$$\frac{a_n^2}{\beta_n} = \frac{e_n}{d_n} = -\left[\frac{(\sigma_0 + i\epsilon_0\omega)\alpha \dfrac{\hat{I}_n'(\alpha)}{\hat{I}_n(\alpha)} - (\sigma + i\epsilon\omega)(n+1)}{(\sigma_0 + i\epsilon_0\omega)\alpha \dfrac{\hat{I}_n'(\alpha)}{\hat{I}_n(\alpha)} + (\sigma + i\epsilon\omega)n}\right] \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)}, \tag{15b}$$

where $\alpha = (i\sigma\mu\omega - \epsilon\mu\omega^2)^{1/2} a$. Since displacement currents may be safely neglected (i.e. $\sigma \gg \epsilon\omega$) the arguments of the Bessel functions are $\sqrt{i}\,|\alpha|$, where $|\alpha| = (\sigma\mu\omega)^{1/2} a$. Furthermore, $|\sigma + i\epsilon\omega| \gg |\sigma_0 + i\epsilon_0\omega|$ in most cases of practical interest, thus:

$$\frac{a_n^1}{\alpha_n} \cong -R_n \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)} \tag{16a}$$

and

$$\frac{a_n^2}{\beta_n} = \frac{e_n}{d_n} \approx \frac{\hat{J}_n(k_0 a)}{\hat{H}_n(k_0 a)} \frac{n+1}{n}, \tag{16b}$$

where R_n has been discussed on previous occasions (Wait 1953 and Ward 1959). (In the earlier notation $R_n = 3(M_n + iN_n$.)

Thus finally, for the magnetic modes,

$$\pi_z^1 = -\frac{Ids \sin\psi \sin\phi}{4\pi} \sum_{n=1}^{\infty} R_n \frac{a^{2n+1} P_n^1(\cos\theta)}{n(n+1) b^{n+1} r^{n+1}} \tag{17a}$$

and, for the electric modes,

$$\pi_z^2 = -\frac{Ids \sin\psi \cos\phi}{4\pi(\sigma_0 + i\epsilon_0\omega)} \sum_{n=1}^{\infty} \frac{a^{2n+1}}{b^{n+2} r^{n+1}} P_n^1(\cos\theta) \tag{17b}$$

$$+ \frac{Ids \cos\psi}{4\pi(\sigma_0 + i\epsilon_0\omega)} \sum_{n=1}^{\infty} \frac{a^{2n+1}}{b^{n+2} r^{n+1}} \frac{n+1}{n} P_n^1(\cos\theta).$$

DISCUSSION OF RESULTS

It is immediately evident that both electric and magnetic modes are excited. In fact, the terms corresponding to $n = 1$ are dipole modes whereas $n = 2, 3, 4, \cdots$ etc. are the multipole modes. In the special case of a purely radial dipole ($\psi = 0$), only a set of electric dipole and multipole modes are excited.

The explicit expressions for the field components are easily obtained by carrying out the operations indicated in equation (1a) and (1b). One interesting feature of this general solution is that the electric dipole and multipole modes are not frequency dependent—at least to the approximation that the external wave length is large and the body is highly conducting. Furthermore, to this same approximation, the secondary field from these electric modes are in-phase with the exciting field. On the other hand, the magnetic dipole and multipole modes are quite frequency dependent since the quantity $|\alpha|$ may be either small or large compared to unity. The secondary response is also out of phase with the exciting field since R_n is a generally complex number. In a practical geophysical scheme, it is often advantageous to measure the phase-quadrature component of the secondary field. In the present case this corresponds to the imaginary component of $\vec{H}^s$. Explicit expressions for these quadrature magnetic field components are:

$$\text{Im } H_r^s = h_r^s = -\frac{3Ids \sin\psi \sin\phi}{4\pi} \sum_{n=1}^{\infty} N_n \frac{a^{2n+1} P_n^1(\cos\theta)}{b^{n+1} r^{n+2}}, \tag{18a}$$

$$\text{Im } H_\theta^s = h_\theta^s = \frac{3Ids \sin\psi \sin\phi}{4\pi} \sum_{n=1}^{\infty} N_n \frac{a^{2n+1}}{(n+1) b^{n+1} r^{n+2}} \frac{\partial}{\partial\theta} P_n^1(\cos\theta), \tag{18b}$$

$$\text{Im } H_\phi^s = h_\phi^s = \frac{3Ids \sin\psi \cos\phi}{4\pi \sin\theta} \sum_{n=1}^{\infty} N_n \frac{a^{2n+1}}{(n+1)b^{n+1}r^{n+2}} P_n^1(\cos\theta), \tag{18c}$$

where N_n is defined above. It is noted that only the influence of the magnetic modes remain since the imaginary part of the field resulting from the electric modes is zero to within the same approximation.

In order to illustrate more effectively the nature of the solution, it is also assumed that $a^2 \ll rb$. Thus, only the dipole terms (i.e. $n=1$) are important. The explicit expressions for the field components are then given by

$$H_r^s \cong \frac{Idsa^3}{4\pi b^3 r^2}\left[-\left(\frac{b}{r}\right)\sin\psi \sin\phi \sin\theta R_1 + 0 + 0\right], \tag{19a}$$

$$E_r^s \cong \frac{Idsa^3}{4\pi(\sigma_0 + i\epsilon_0)b^3r^3}\left[0 - 2\sin\psi \sin\theta \cos\phi + 4\cos\psi \cos\theta\right], \tag{19b}$$

$$H_\theta^s \cong \frac{Idsa^3}{4\pi b^3 r^2}\left[\left(\frac{b}{r}\right)\sin\psi \sin\phi \cos\theta \frac{R_1}{2} + \sin\phi \sin\psi + 0\right], \tag{19c}$$

$$E_\theta^s \cong \frac{Idsa^3}{4\pi(\sigma_0 + i\epsilon_0\omega)b^3r^3}\left[0 + \sin\psi \cos\theta \cos\phi + 2\cos\psi \sin\theta\right], \tag{19d}$$

$$H_\phi^s \cong \frac{Idsa^3}{4\pi b^3 r^2}\left[\left(\frac{b}{r}\right)\sin\psi \cos\phi \frac{R_1}{2} - \sin\psi \cos\theta \cos\phi + 2\sin\phi \cos\psi\right], \tag{19e}$$

$$E_\phi^s \cong \frac{Idsa^3}{4\pi(\sigma_0 + i\epsilon_0\omega)b^3r^3}\left[0 - \sin\psi \sin\phi - 0\right]. \tag{19f}$$

The factor in square brackets, in each expression, is written as the sum of three parts. The first of these is the influence of the induced magnetic dipole and is proportional to sin ψ. It thus reaches a maximum for a purely tangential dipole and vanishes for a purely radial dipole. The second and third parts in the square brackets are proportional to sin ψ and cos ψ, respectively, and thus they can be identified with the electric dipoles induced in the x and z directions.

ADDITIONAL NOTE

It has been pointed out by Dr. A. A. Brant that in many practical applications, out-of-phase secondary fields arise from the electric modes. Ground conductivities may range from 10^{-3} to 10^{-2} mhos per meter, the distances involved between current dipole and detector may be around 300 meters, and frequencies in use could be of the order of 100 cycles. Phase angles involved for the electric modes could thus be approximately $300/\delta$ where δ is the skin depth. In extreme cases, this could be as large as 90°. This fact should be kept in mind in the interpretation of field results.

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GEOPHYSICS, VOL. XXV, NO. 3 (JUNE, 1960), PP. 659–682, 12 FIGS.

SOUND SPEED AND ABSORPTION STUDIES OF MARINE SEDIMENTS BY A RESONANCE METHOD—PART II*

GEORGE SHUMWAY†

Relation of Sound Speed to Sediment Physical Properties

Introduction

The relationships between sound speed and the more important physical properties of unconsolidated sediments have become known in recent years largely as a result of the studies of Hamilton, 1956; Hamilton et al., 1956; Shumway, 1956, 1958; Nafe and Drake, 1957; Sutton, Berckhemer and Nafe, 1957; and Laughton, 1954, 1957. The suite of samples used in this study is larger and more varied than the suites used in any of the earlier studies, and the measurements probably were more carefully taken. A large number of shelf and harbor sediments were used in addition to sediments from deeper water in the Pacific and Arctic Oceans.

Porosity stands out as the most important single factor causing variations in compressional sound speed in unconsolidated sediments; this is because the difference in compressibility between water and mineral grains is so great, and porosity is a measure of the relative amounts of fluid and solid present. Second in importance is the factor which produces a rigidity in the sediment; this appears to be related to the abundance of coarse grains. Pressure and temperature rank third and fourth, respectively. Next in importance is the compressibility of the grain aggregate, determined from compressibilities of individual minerals. Differences in densities of the mineral grains most abundantly found in sediments are small; hence the aggregate sample grain density changes little from sample to sample. The effect of grain density variations are not negligible, however. Grain shape and the spatial inter-relationship of grains are factors undoubtedly of importance, for they not only determine the characteristics of fluid flow past the grains, but also they determine (along with grain size) the extent to which a frame incompressibility and a rigidity develop between grains. Unfortunately, it is next to impossible to describe the spatial distribution of particles and the nature of the pore space between them for a given natural sediment.

Considering the extremes of porosity (0.85–0.40), hydrostatic pressure (0–1100 bars), temperature (−2°C.–35°C.), and mineral composition (all quartz —all kaoline-like clay) which nature might provide in the marine sediment en-

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vironment, sound speed is affected by individual factors as follows:

Factor	*Percent change in sound speed*
Porosity	16
(Rigidity)	(10–20)
Pressure	11
Temperature	7
Grain aggregate compressibility	3

Pressure and temperature effects

Temperature and pressure changes occur in a sediment sample when it is brought from the sea floor to the laboratory. If the acoustic properties of sediments *in situ* on the sea floor are to be inferred from laboratory measurements, then it is necessary to appreciate the effects of these factors. With the knowledge at hand of how to relate laboratory measurements at atmospheric pressure and room temperature to probable *in situ* values, it becomes possible to understand the interrelationships of acoustic, sediment texture, and other physical properties of sediments *in situ*, on the basis of laboratory studies.

The effects of hydrostatic pressure on the speed of sound in unconsolidated ocean sediments are considered by Laughton (1957). His results showed a compressional velocity increase of about three or four percent in going from one bar pressure to 390 bars; this change is about the same as for sea water alone.

Pressure studies were not undertaken as part of this study because the compliant-walled resonant chamber is not adaptable to pressure work. The resonant chamber could be placed in a pressure vessel of larger volume, but a liquid such as water would be unsuitable as a pressure medium because the external walls of the resonant chamber must be unloaded; even gas, such as nitrogen, under pressures of a few hundred bars, is dense enough to complicate the system greatly.

The effect of temperature on compressional speed is considerable, amounting to an increase of 10 percent to 15 percent in going from 0°C. to about 60°C. This is readily determined by using equations (1) or (2) with appropriate densities and compressibilities, and it has been verified experimentally by the writer (1958) for a number of typical sea floor sediments.

Effects of other physical properties

Introduction.—The interrelationships of wet density, porosity, and the more important textural properties of sediments have been discussed at some length by Hamilton et al. (1956), Hamilton and Menard (1956), Nafe and Drake (1957), Sutton, Berckhemer and Nafe (1957), and others; hence a general discussion is not called for here. The relationships between sound speed and those parameters which appear to be most important on the basis of the earlier work can be considered immediately.

Porosity.—Data for 110 samples are used to show the relationship of porosity to sound speed (Figure 1). The mean temperature at which these samples were

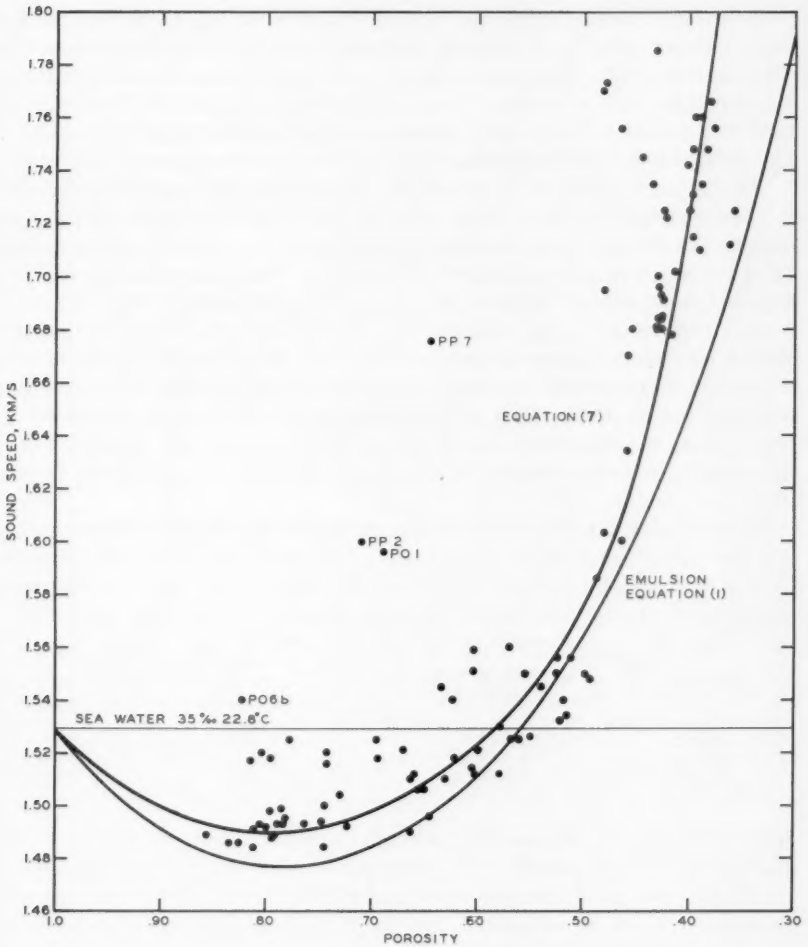

FIG. 1. Sound speed vs. porosity for unconsolidated marine sediments.

measured was 22.79°C. and the standard deviation of temperatures from this mean was 2.064°C. Sound speed in sea water of 35°/$_{oo}$ salinity at this temperature is 1.5293 km/sec (Del Grosso, 1952). More than a third of the sediment speed values lie below this water value. Measured speeds ranged from 1.484 km/sec to 1.785 km/sec; measured porosities ranged from 0.357 to 0.856. It is evident that although sound speed increases as porosity decreases, the relationship is not linear.

Urick (1947) was one of the first to take experimental data on the relationship between sound velocity and porosity. He measured velocity in dilute suspensions of kaolin, by means of an interferometer, and found results which agreed well with predictions using the emulsion equation of Wood (equation 1). This equation predicts a parabolic curve with a minimum sound speed at a porosity of about 0.8, this minimum speed being about three percent below the speed in water alone.

The effect of porosity alone on sound speeds in sediments is given by equation (1), with all grains consisting of one mineral. Using quartz as the mineral, speeds range from 1.476 km/sec at a porosity of about 0.79 to a value 16 percent higher, 1.71 km/sec at a porosity of about 0.35 (Figure 1). The speed variation is similar if typical minerals other than quartz are considered (Hamilton, 1956).

The curve representing equation (1), with quartz as the mineral, lies significantly below the measured values of the sands, in the porosity range 0.35 to 0.45, because rigidity has been neglected. The curve lies significantly below the measured values of the clays and finer silts, in the porosity range 0.65 to 0.85 because here the sediment particles consist dominantly of clay minerals rather than quartz, and the compressibilities of clay minerals are appreciably smaller than the value for quartz.

Mineral grain compressibilities.—The effects of mineral grain compressibility on sound speed are predicted by equation (1), if grain density is held constant. Using a grain density of 2.7 g/cm³ for quartz, calcite, and "clay," the following sound speeds are predicted by equation (1) for grains in sea water at 22.8°C:

Mineral	Compressibility cm²/dyne	Sound Speed, km/sec	
		0.70 porosity	0.40 porosity
quartz	2.70×10^{-12}	1.476	1.639
calcite	1.35×10^{-12}	1.486	1.677
"clay"	1.0×10^{-12}	1.488	1.687

At 0.40 porosity the difference between the values for quartz and "clay" sediments is about three percent, and at 0.70 porosity it is less than one percent.

Rigidity and grain size.—In the writer's (1958) study on the effects of temperature on sound speed a small, but not negligible, rigidity had to be introduced to make the theoretical curves fall near the experimental data. The existence of this rigidity is acknowledged by a number of papers already mentioned, but no attempt has been made to relate it to the textural properties of the sediment. In addition to rigidity, a frame bulk modulus is involved here. The two are difficult to separate in this case, and in the following discussion they are considered together under the name of rigidity.

The rigidity of a given sediment increases as it consolidates, loses water, and develops intergranular cementation. These are the changes that take place as a sediment ages and becomes buried under younger materials. Laughton (1955, 1957) made laboratory compaction studies of sediments and the changes in the

acoustic properties of the sediments as compaction proceeded. Consolidation effects are not considered in the present study.

This study deals only with unconsolidated surface sediments—sediments which are compacted only to the extent that is natural as they accumulate at the surface of the sea floor and become buried by no more than about one meter of sediment. In these materials the rigidity modulus must be related to the textural properties of the sediment.

For sediments in general it may be said that as median, mean or mode grain size diameter increases, porosity decreases. The suite of samples used in this study exhibit this relationship well. The relationship is approximately linear when grain size is measured in phi units. (Diameter in phi units equals $-\log_2 r$ where r is diameter in mm.) The porosity-median diameter relationship has a positive correlation coefficient of 0.948. The porosity-mean diameter relationship (Figure 2) has a slightly higher positive correlation coefficient, 0.959.

As a result of this marked correlation between porosity and central tendency, a distinctive relationship between sound speed and mean grain diameter is found (Figure 3). It may be said that, in general, the smaller the median or mean di-

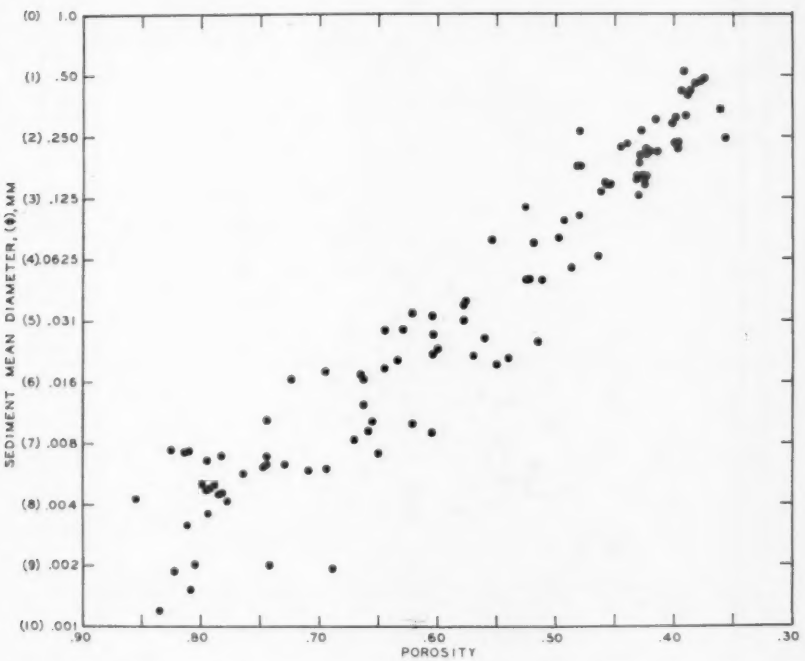

FIG. 2. Mean diameter vs. porosity for unconsolidated marine sediments.

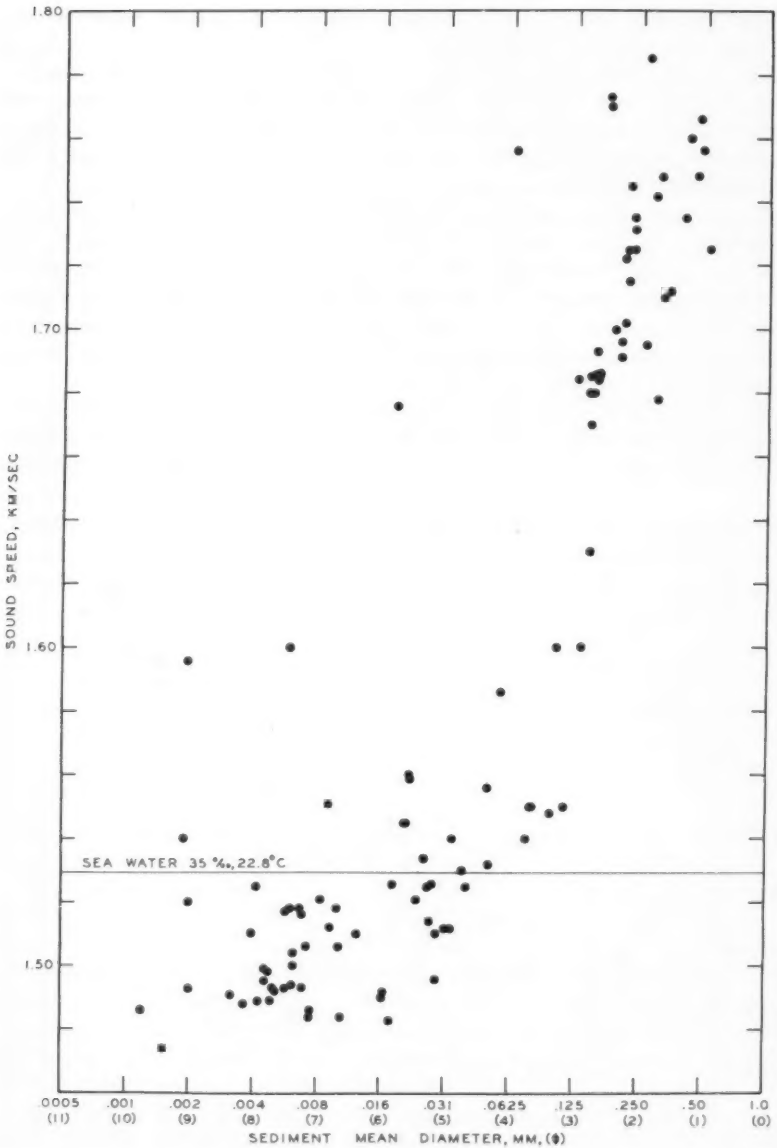

FIG. 3. Sound speed vs. sediment mean diameter.

ameter, the lower the sound speed. The relationship is more pronounced for mean than for median diameter. The relationship is not linear, for it is mainly due to the non-linear sound speed-porosity relationship. In addition to the porosity effect is the effect of the rigidity, which apparently increases as porosity decreases and grain size increases.

The degree to which the distribution of grain sizes in a sediment is sorted can be expressed by phi deviation measure (Inman, 1952). The relationship between this measure and grain size central tendency for the suite of sediments used in this study (Figure 4) is typical for sediments in general (e.g. Inman and Chamberlain, 1955). The sediments with poorest sorting are in the silt group. The sediments with best sortings are the sands. The number of clay samples is relatively small, but the few samples available suggest that the clay group of sea-floor sediments may be better sorted than the silts.

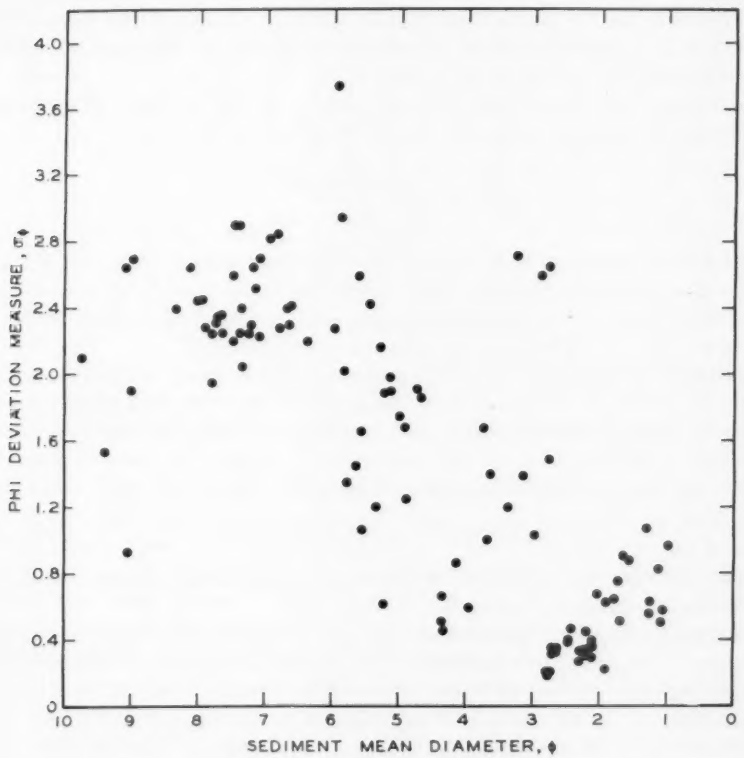

FIG. 4. Phi deviation measure vs. sediment mean diameter.

The general sediment contains both particles in suspension and particles in contract. Throughout the sediment isolated groups of particles-in-contact are found which give local regions where rigidity is important. The effective rigidity of the sediment, therefore, should be a function of the volume fraction occupied by these particles-in-contact and their enclosed interstices. In general it is the larger particles, i.e., the sands and coarser silt particles, which contact one another, while the finer particles, many of which are in the colloidal state, remain effectively in suspension. The volume fraction or weight fraction of coarse grains in the sample therefore might, in itself, be related to the rigidity.

For the sediments involved in this study the volume fraction of the wet sediment occupied by grains coarser than silt size, i.e. coarser than 0.0625 mm, was determined by multiplying the particle concentration, $(1-\eta)$, by the weight fraction of grains coarser than this diameter, ψ, as given by the mechanical analysis. This assumes that there is little difference between weight fractions and volume fractions for the grains alone. For the sediments involved this assumption is valid. A pronounced inverse relationship between porosity and the sand volume fraction is exhibited by the data (Figure 5).

Assuming that the sediment volume fraction of sand grains is proportional to the rigidity modulus, equation (5) can be written in the form

$$C_{ws}^2 = \frac{K_{ws} + b(1-\eta)\psi}{\sum f_{si}\rho_{si} + f_w\rho_w}, \tag{7}$$

where b is a constant. This equation fits the experimental data considerably better than does equation (1), when a value of 0.8 is used for b, appropriate mineral densities and compressibilities are used, and when ψ is given values of 1.0 at $\eta=0.4$, 0.3 at $\eta=0.525$, and zero at $\eta=0.8$ (Figure 1).

Discussion.—Sutton et al. (1957) performed an elaborate statistical analysis on the data from 37 samples they studied. By use of the multiple linear regression statistics they developed an equation relating the dependent variable, sound velocity in km/sec (C_{ws}), to the independent variables phi median diameter (Md_ϕ), percentage of material soluble in HCl (γ), and porosity (η):

$$C_{ws} = 2.093 - (.0414 \pm .0060)Md_\phi + (.00135 \pm .00038)\gamma - (.44 \pm .15)\eta. \tag{8}$$

A multiple correlation coefficient of 0.90 was found for sound velocity in relation to the three independent variables.

An analysis of this type must be viewed with caution. The interrelationships between the variables in a multiple linear regression equation should be linear, yet the ones used are not all linear. Although the analysis accounts for the interdependence of the variables involved, there is no assurance that the variables used are the significant ones. For instance, in the present study the good correlation between porosity and mean (or median) diameter (Figure 2), and between porosity and sand content (Figure 5) result in a strong correlation between

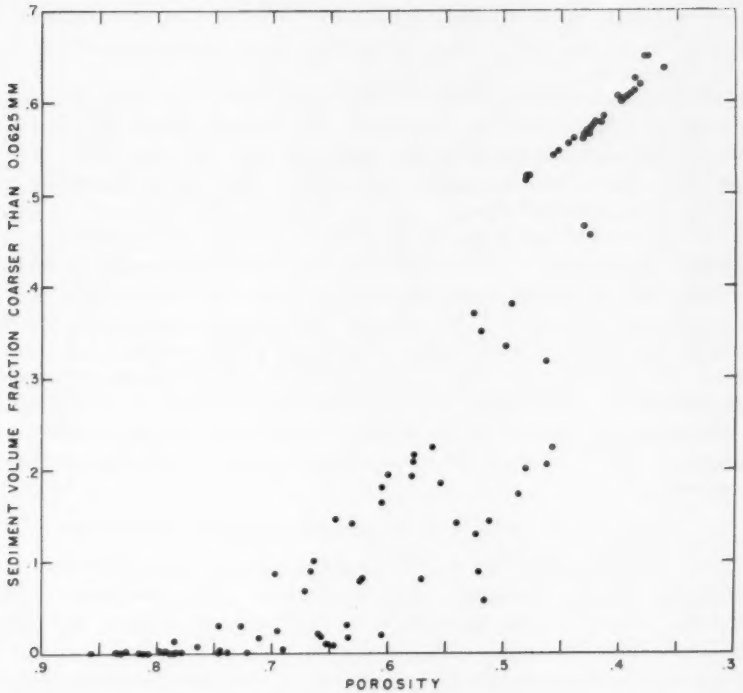

FIG. 5. Sediment sand content vs. porosity.

mean (or median) diameter and sand content. Thus, the median diameter effect implied by equation (8) may in truth be the rigidity effect related to the content of coarse grains and probably also other factors related to the content of coarse grains.

In spite of such objections, there may be some merit in determining a multiple linear regression equation; hence an analysis similar to that of Sutton et al., but not as comprehensive, was made using data from 108 samples of the present study. The independent variables used differed somewhat from those of Sutton et al. Sound speed in km/sec (C_{ws}) again was taken as the dependent variable; independent variables consisted of porosity (η), phi mean diameter (M_ϕ), and phi deviation measure (σ_ϕ). Statistical data are summarized in Table II.

Phi mean diameter rather than phi median diameter was used because it correlates better with sound speed and with porosity. Phi median diameter, however, correlates slightly better with phi deviation measure than does phi mean diameter. The resulting multiple linear regression equation is

$$C_{ws} = 1.5955 - 0.0287(M\phi - \overline{M_\phi}) - 0.3658(\eta - \bar{\eta}) + 0.0472(\sigma_\phi - \bar{\sigma}_\phi), \quad (9)$$

or

$$C_{ws} = 1.87295 - 0.0287M_\phi - 0.3658\eta - 0.0472\sigma_\phi. \quad (10)$$

The multiple correlation coefficient, $R_{C^0 M_\phi \eta \sigma_\phi}$, equals 0.959, which is higher than the value of 0.90 obtained by Sutton et al. The standard error of estimate, S_e, equals $(0.0007744)^{1/2}$ or 0.027828, which is lower than the value of 0.054772 obtained by Sutton et al. This means that the standard error for the prediction of sound speed by means of equation (10) is about 28 m/sec.

The best expression relating sound speed to the more important independent variables is equation (7). The problem of relating the rigidity modulus (and frame incompressibility) to measurable sediment variables remains unsolved, however. In equation (7) it is assumed that the combined effect of these moduli is proportional to the content of sand in the sample. This simple assumption is merely a step in the right direction, for undoubtedly a number of factors are involved. The problem has been avoided in the development of existing published theories on sound propagation in composite media. The effect of frequency on sound speed (Laughton, 1957) is so small that it can be neglected for any practical application of equation (7).

RELATION OF ABSORPTION TO SEDIMENT PHYSICAL PROPERTIES

The relationship between absorption and porosity (Figure 6) exhibits an absorption maximum for sediments of intermediate porosity; absorptions are highest in the porosity range 0.45 to 0.60, where the dominant sediment type is coarse silt. The highest absorption measured was 25.1 db/m, and the lowest was 0.66 db/m. In general, the lowest absorption values were found in those sediments which had the highest porosity, the clays and finer silts. Due to the high degree

TABLE II

Statistical Data

Number of observations, $N = 108$ S designates a sum

Sound Speed km/sec	$S(C) = 172.317$	$\overline{C} = 1.595527$
Phi Median Diameter	$S(Md_\phi) = 483.28$	$\overline{Md_\phi} = 4.4748$
Phi Mean Diameter	$S(M_\phi) = 515.51$	$\overline{M_\phi} = 4.77324$
Porosity	$S(\eta) = 62.294$	$\overline{\eta} = 0.57680$
Phi Deviation Meas.	$S(\sigma_\phi) = 161.61$	$\overline{\sigma_\phi} = 1.49639$
Standard deviations	$\sigma_C = 0.098.5$	$\sigma_{M_\phi} = 2.4446$
$\sigma\eta = 0.15028$	$\sigma_{\sigma_\phi} = 0.91823$	$\sigma_{Md_\phi} = 2.2894$
Correlation coefficients		
$r_{CM_\phi} = -0.914$	$r_{M_\phi \eta} = +0.959$	$r_{Md_\phi 3} = -0.815$
$r_{C\eta} = -0.891$	$r_{M_\phi \sigma_\phi} = +0.766$	$r_{Md_\phi \eta} = +0.948$
$r_{C\sigma_\phi} = -0.556$	$r_{\eta\sigma_\phi} = +0.803$	$r_{Md_\phi \sigma_\phi} = +0.804$
Standard error of estimate	$S_e = (0.0007744)^{1/2} = 0.027828$ km/sec	
Multiple correlation coefficient	$R_{C^0 M_\phi \eta \sigma_\phi} = 0.959$	
$S(C^2) = 275.97712$	$S(\sigma_\phi^2) = 332.8909$	$S(C\sigma_\phi) = 252.44093$
$S(Md_\phi^2) = 2713.9828$	$S(\eta\sigma_\phi) = 105.19227$	$S(Md_\phi \eta) = 313.50702$
$S(M_\phi^2) = 3106.0714$	$S(C\eta) = 97.71919$	$S(\eta M_\phi) = 335.39041$
$S(\eta^2) = 38.36993$	$S(CM_\phi) = 799.57545$	$S(M_\phi \sigma_\phi) = 975.0575$
		$S(Md_\phi \sigma_\phi) = 905.6357$

of correlation between porosity and grain size central tendency, the relationship between median grain diameter and absorption also shows a maximum (Figure 7).

In addition to the sediment data plotted on the absorption-porosity diagram (Figure 6), four absorption values for rocks of essentially zero porosity and a value for quartz have been plotted. These rock values were obtained from Ide's (1937) measured the values of mechanical Q through the relation $\alpha = \pi(\lambda/Q)$ where α is sound absorption in nepers per unit length and λ is the wave length. His measurements were made on rock cylinders 5.08 cm in diameter and 25.4 cm long driven as bar resonators; hence the fundamental resonances were in the audio range. For comparison with the resonant chamber measurements, his reported values were corrected to a frequency of 24 kc/sec by assuming a first power frequency dependence (Knopoff and MacDonald, 1958). Unfortunately, similar measurements have not been made for water-saturated sedimentary rocks, to fill in the gap between zero and 0.35 porosity values.

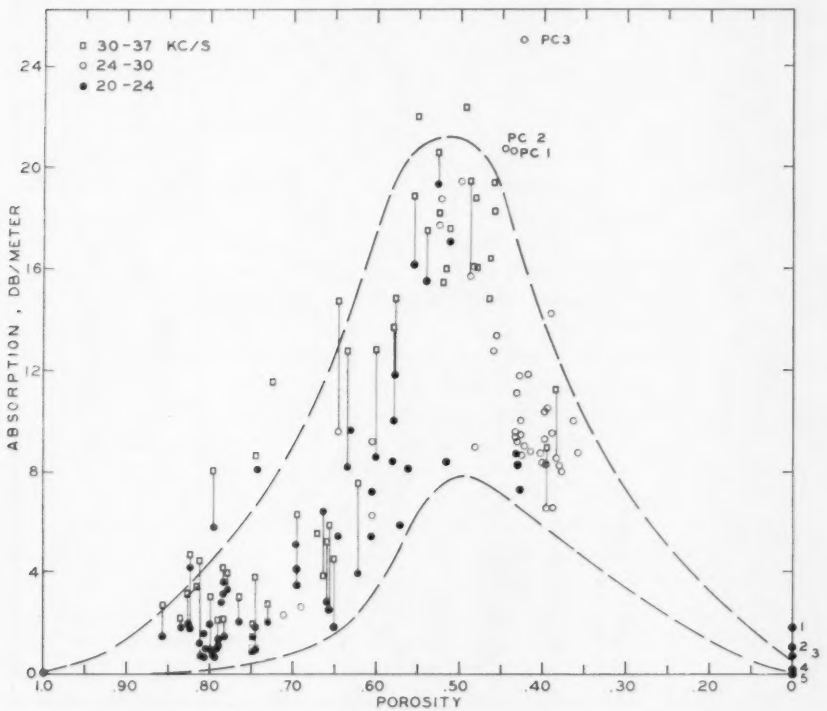

FIG. 6. Sound absorption vs. porosity for unconsolidated marine sediments. Numbered values at zero porosity are (1) Quincy granite, (2) quartzite sandstone, (3) French Creek norite, (4) Vinal Haven diabase, (5) quartz, of Ide (1937), corrected to a frequency of 24 kc/s.

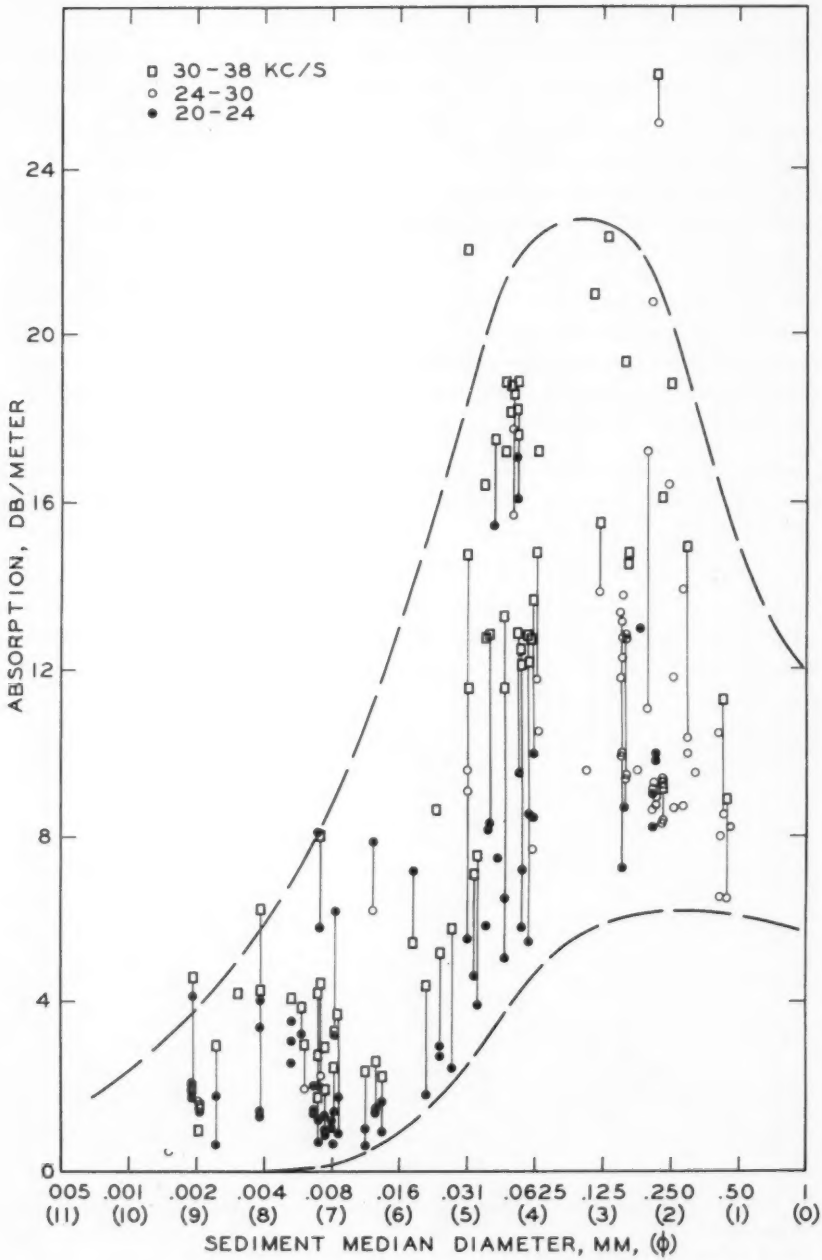

Fig. 7. Sound absorption vs. median diameter for marine sediments.

Most absorption values lie within the two arbitrarily drawn dashed curves on Figure 6. At frequencies between 20 kc/sec and 40 kc/sec most natural sea floor sediments probably have absorption values within the limits defined by these curves. The curves have been drawn to include the porosity region below 0.35, where lithified sediments rather than unconsolidated ones are found. For reasons that will be given below, it is suggested that this curve may predict the general range of values for these lithified sediments also.

Particularly high absorption values were found for three Panama City samples, PC1, PC2, and PC3, whereas normal values were found for the other samples from the same locality, PC5a, PC5b, PC5c. The three samples with high absorption contained numerous gas bubbles along the side of the container and contained many roots scattered throughout the sample. These roots were hollow and contained gas bubbles. When pieces of these roots were squeezed between the fingers visible bubbles were released. The samples with normally low absorption values were samples from which these roots had been removed and from which had been removed any gas bubbles that would float to the surface as a result of agitation of the sediment under water.

An explanation for the absorption maximum found for sediments of intermediate porosity and intermediate grain size can be found through consideration of "accoustically effective" surface areas of particle aggregates. Urick (1948) studied absorption in suspensions of irregular particles, and noted that theory would have this absorption be due primarily to viscous losses resulting from relative motion of particles and fluid (equation 6). He found experimentally that for particles of a given size, absorption increases linearly as the volume concentration increases from zero to about 15 percent, but then drops off as concentration increases further, presumably as a result of particle interaction. Using particle concentrations of one percent by volume, and making measurements in the megacycle range, he found that as particle diameter decreases linearly from 10 to 0.9 microns, absorption increases linearly. According to theory (second term of equation 6) this linear relationship would fail to hold for smaller particles, Urick's explanation being that very small particles undergo less motion relative to water than do somewhat larger particles. Urick comments: "Extremely small particles tend to move to and fro along with the liquid in the sound field. . . . As the particle size increases the particles lag more and more behind the movement of the fluid; but at the same time the total surface area of particles decreases with increasing size if the volume concentration remains constant. These opposing factors result in an absorption maximum." Two important principles thus are suggested: (1) absorption is an additive process; (2) absorption depends on the total acoustically effective surface area of particles in suspension.

In the lower porosity materials considered in the present study, namely sands and lithified sands, suspended particles are of negligible importance. Fluid exists in a framework of grains, and moves relative to this framework under sonic agitation, producing viscous losses. This absorption will depend on the acoustically

effective channel wall area and will be approximated closely by the total surface area of the particles. The acoustic surface area for a fluid-filled granular aggregate or a porous solid is here defined as the area of a flat plate lying parallel to the direction of propagation which yields an energy loss due to viscosity equivalent to the viscous loss in the porous material.

For any sediment the total acoustic surface area, A_s, can be computed by dividing the sediment into size fractions, determining the number of particles in each fraction assuming spherical particles, determining the total particle surface area of each fraction, and then applying a correction factor for acoustically small particles based upon the second term of equation (6).

For a volume, v, of wet sediment of porosity η consisting entirely of grains of radius r_i, the surface area, A, is

$$A_i = \frac{(1-\eta)v4\pi r_i^2}{(4/3)\pi r_i 3} = \frac{3(1-\eta)v}{r_i} . \tag{11}$$

The total grain volume is $(1-\eta)v$. If grains of a number of sizes are present rather than grains all of one size, and the volume fraction of grains of radius r_i is represented by $(1-\eta)vf_i$, then the total surface area for a sediment is

$$A = \sum_{i=1}^{n} \frac{3(1-\eta)vf_i}{r_i} . \tag{12}$$

After a grain size analysis has been done for a sediment, the surface area computation can be done fairly easily. In the size analysis the sediment is divided into size fractions and the relative proportions by weight of these fractions are determined. For various size fractions, weights and volumes will be proportional if all grains are of the same material; inasmuch as the densities of quartz, calcite, and "clay" are close to each other, the proportionality will be practically valid for sediments composed of any of these materials. Therefore the weight fractions determined in the size analyses may be used for the f_i values. Values of r_i are taken from the mean radii of the size fractions, which lie midway between the extreme radii of the fractions. Size fraction radii limits usually are taken at whole or half phi intervals, and mean values in millimeters rather than mean phi values should be used.

For equation (12) to be useful for all sediments, factors F_i must be introduced to give "effective" areas for the smaller particles. The equation, for acoustic surface area, A_s, is

$$A_s = \sum_{i=1}^{n} \frac{3(1-\eta)F_i f_i v}{r_i} . \tag{13}$$

Values for the F_i are determined in the following manner. The second term of equation (6) is used in the form which follows to determine the absorption per unit volume for suspensions of constant composition but of varying particle size:

$$\alpha = \frac{4\pi r^3 n}{3}\left[\frac{2\pi}{\lambda}\left(\frac{\rho_s}{\rho_w} - 1\right)^2 \frac{s}{s^2 + (\rho_s/\rho_w + \tau)^2}\right]. \tag{14}$$

If, for acoustically large particles, absorption is directly related to surface area, then using equation (11) yields

$$\begin{aligned} \alpha &= KA \\ &= K[3(1 - \eta)v/r_i], \end{aligned} \tag{15}$$

where K is an undetermined constant. For particles not large acoustically a factor F_i would appear on the right side of (15). By dividing equation (14) by equation (15) with the F_i factor introduced, the F_i values are obtained with the expression

$$F_i = K' \frac{(\sigma - 1)^2(1 + 1/r\beta)}{\beta[s^2 + (\sigma + \tau)^2]}, \tag{16}$$

where K' is another undetermined constant.

Actual values for the F_i were found graphically. Equation (14) was plotted for quartz particles with a constant concentration of one percent, a frequency of 30,000 c/sec, a wave length for sound of 5 cm, and a kinematic viscosity of 0.01 cm²/sec (Figure 8). On the same graph, equation (14) is represented by the straight line which is asymptotic to equation (13) in the region of large particle diameters. For given values of particle diameter the ratio of the ordinates of these two curves provides the F_i. The following values were obtained:

Size range phi	*Mean diam. mm*	*Sediment name*	*F*
4–5	0.04688	Coarse silt	0.91
5–6	.023438	Medium silt	0.78
6–7	.011718	Fine silt	0.67
7–8	.005859	V. fine silt	0.33
8–9	.0029297	Coarse clay	0.089
9–10	.0014648	Medium clay	0.0125
10–11	.0007324	Fine clay	0.00214

Using the F_i thus obtained, acoustic surface areas were computed for the sediments of this study (Table I). Surface areas computed in this manner for the finer sediments are considerably smaller than the values obtained without use of the correction factors. For silts and clays it is difficult to compute a surface area without these correction factors because a significant portion of the total area of such sediments is contributed by particles smaller in diameter than the limiting diameter of the usual grain size analysis. The total surface areas of some deep-sea sediments were measured by Kulp and Carr (1952) using a gas-absorption method. Their values ranged between about 5 and 50 m²/gm of dry sediment. Nelson and Hendricks (1943) and Diamond and Kinter (1958) measured by an absorption method the surface areas of some clay soils and obtained results of the same order of magnitude. In comparison, the acoustic areas computed in the present study have values of about 0.05 m²/gm of dry sediment. Thus total sur-

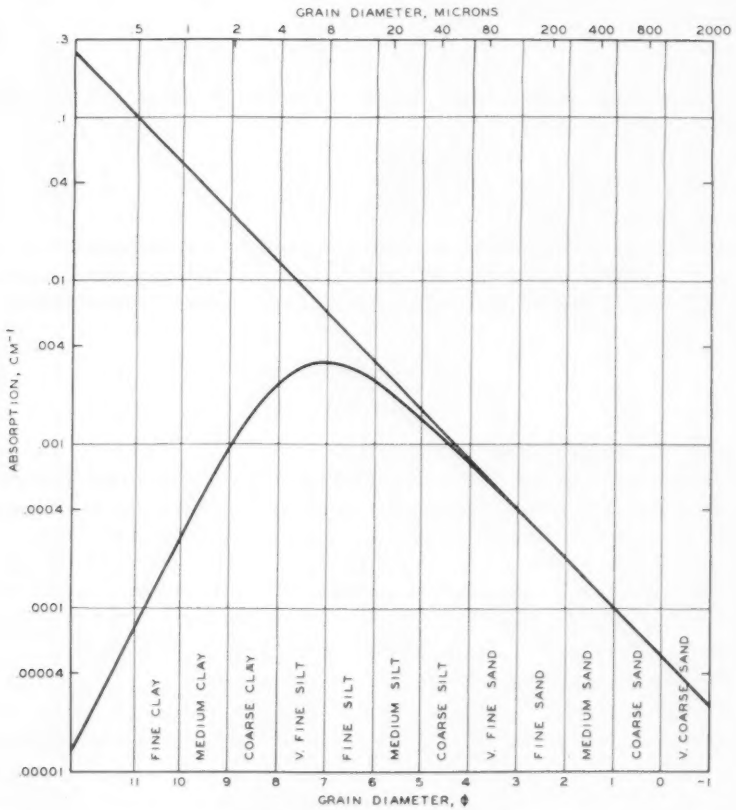

FIG. 8. Absorption per cm at 30 kc/s for a 1 percent by volume suspension of quartz particles in water as a function of grain diameter. The curve is a plot of equation (14). The straight line is asymptotic to the curve.

face areas for silts and clays are about 100 to 1000 times larger than acoustic surface areas, at a frequency of 30 kc/sec. At lower frequencies the acoustic areas would be smaller still.

The computed acoustic surface areas exhibit maxima for sediments of intermediate porosity (Figure 9) and intermediate grain size (Figure 10). These maxima, however, do not coincide exactly with the absorption maxima, but lie somewhat on the high-porosity, smaller-median-diameter side. Furthermore, the acoustic surface areas for the sands are smaller than for the clays and fine silts, yet sand absorption values are higher. These features suggest that absorption and acoustic surface area may be related through an additional factor, or factors, and

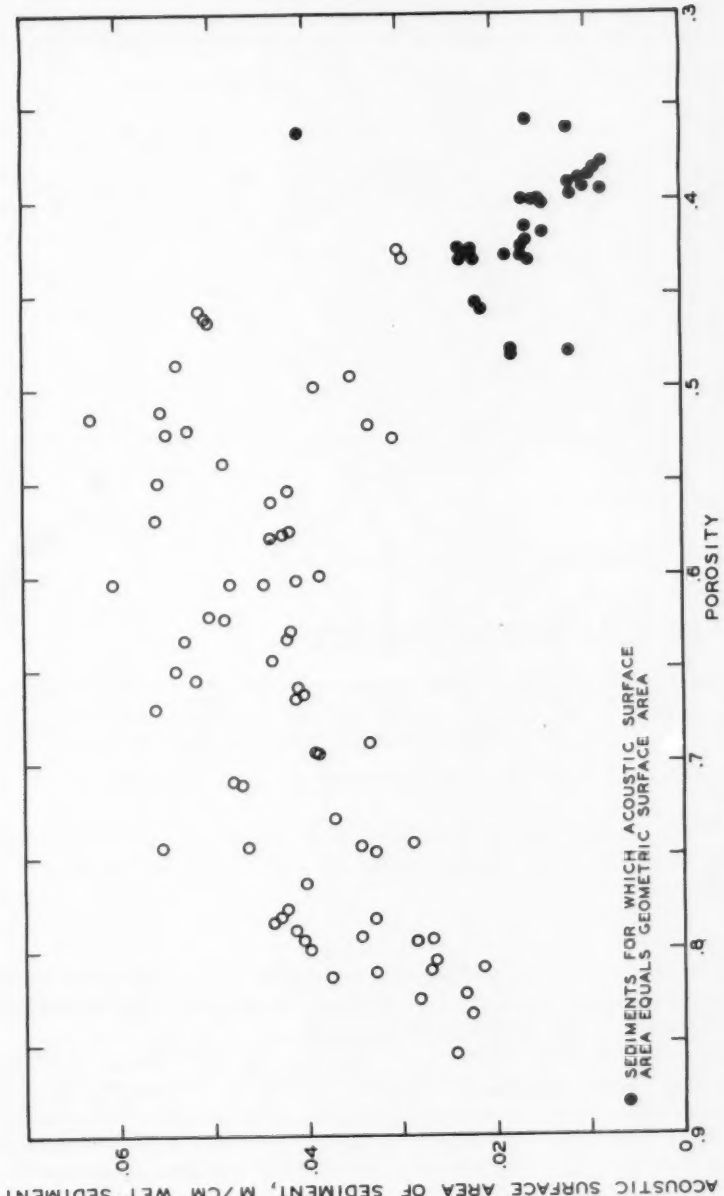

FIG. 9. Acoustic surface area of sediments vs. porosity, at 30 kc/s.

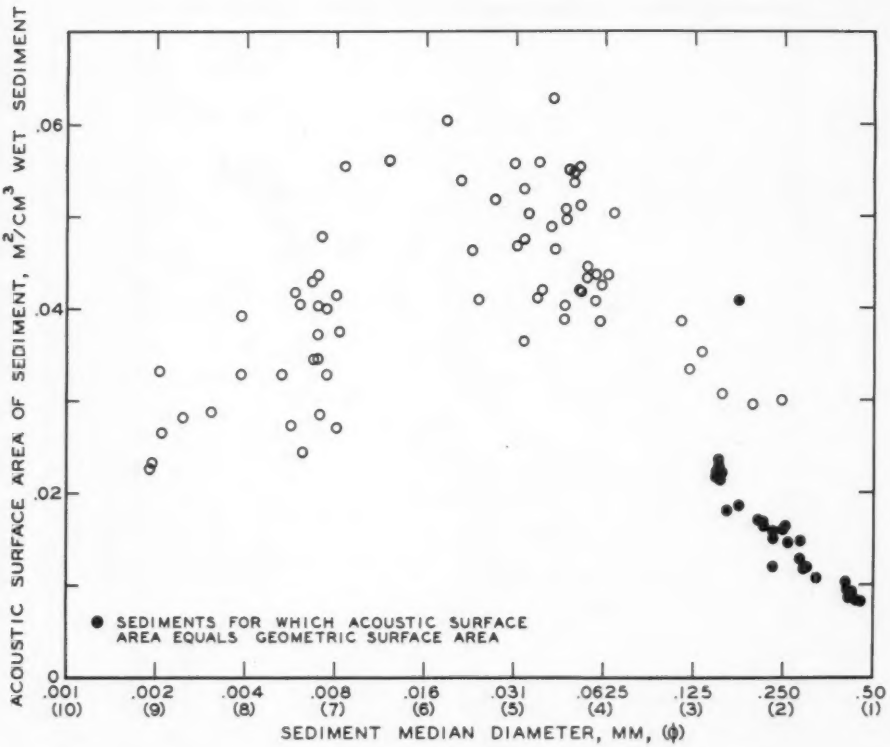

FIG. 10. Acoustic surface area of sediments vs. median diameter, at 30 kc/s.

that this factor may vary with porosity and grain size in a systematic manner.

Let M be the factor relating absorption and acoustic surface area in the following manner:

$$\alpha = MA_s. \tag{17}$$

Values of M were determined from measured absorption and computed acoustic surface area values (Figure 11). The M values increase in a regular manner as porosity decreases, and are frequency-dependent.

The similarity of the M-porosity relationship, and the sand-content-porosity relationship (Figure 5) suggests a possible physical explanation for M. In dry crystalline rocks elastic wave energy absorption is considerably higher than it is in isolated crystals of the minerals involved (Ide, 1937; Birch and Bancroft, 1938a, b; Birch et al., 1942). Crystalline rocks and lithified sedimentary rocks

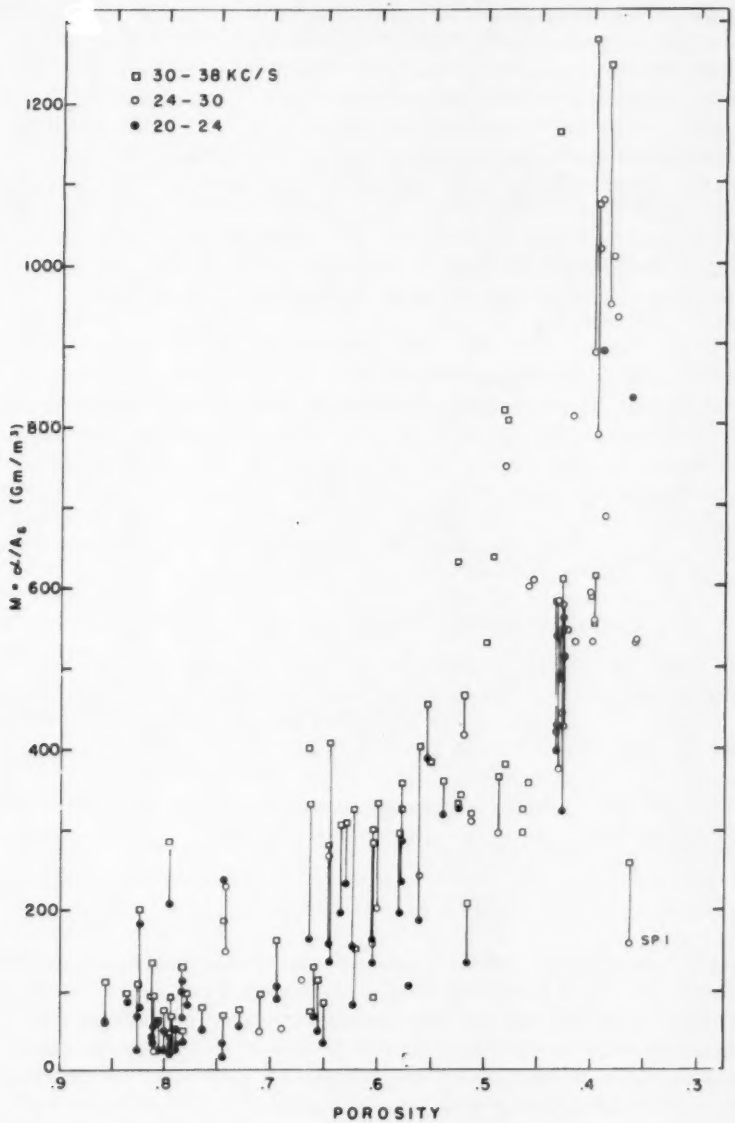

FIG. 11. Absorption factor, M, vs. porosity.

have mechanical Q values of the order of 10^2 at atmospheric pressure, while isolated quartz crystals have yielded Q values as high as 10^7 (Green, 1955). Absorption in the rock materials is due mainly to processes at mineral grain boundaries. By applying a pressure of about 4,000 bars to a rod of granite, Birch and Bancroft (1938b) increased the experimental Q from 180 to 1,200. In an unconsolidated sediment containing grains in mutual contact similar inter-grain losses are to be expected, whereas such losses would almost be non-existent in a suspension of colloidal clay particles. The total of inter-grain losses in a sediment should be approximately a function of the fractional volume of the sediment occupied by grains-in-contract, and this in turn is approximated by the content of coarse grains, ψ. Thus absorption values might be predicted by the expression

$$\alpha = a\psi A_s, \tag{18}$$

where a is a frequency-dependent number.

The M-porosity relationship is pronounced, and this adds considerable support to the contention that acoustic losses in unconsolidated water-saturated sediments are due in large part to viscous losses occurring at grain boundaries, and in channels between grains. The factor M is important also, however, in determining the total absorption. Probably M is a more complicated function than that suggested by equations (17) and (18), and ψ gives only a rough measure of it.

ABSORPTION DEPENDENCE ON FREQUENCY

A theory of absorption applicable to a general sediment containing both suspended particles and "particles-in-contact" probably does not exist. However, due to the additive nature of the absorption process, some general predictions about the dependence of absorption on frequency in a general sediment can be made by adding the effects due to particles in both conditions.

Equation (14), derived for suspended particles assuming energy loss through viscosity, calls for a frequency dependence of the form

$$\alpha = \frac{m + nf^{1/2}}{a + bf^{-1/2} + cf^{-1} + df^{-3/2} + hf^{-2}}, \tag{19}$$

where $\alpha, f, a, b, c, d, h, m$, and n are, respectively, the absorption factor, frequency, and constants. Biot's (1956a, b) theories for fluid-filled porous solids at frequencies high enough that Poiseuille flow does not hold call for an absorption coefficient proportional to the square root of frequency, and for lower frequencies, where Poiseuille flow does hold, for absorption proportional to the square of frequency. However, in a porous granular material the pore space is irregular in shape, so that at a frequency high enough that Poiseuille flow does hold for the main part of the larger pores there will be regions where it does not hold, such as the space which immediately surrounds the contact area between grains. For the

general sediment, the suspended particle theory would apply in part, together with both the high and low frequency theories of Biot.

If these three theories are simultaneously valid for the general sediment, the consequences would be that: (1) for a given material the frequency dependence of absorption changes with frequency because (a) the acoustic surface area of suspended particles is frequency dependent, and (b) because in pores of irregular shape the relative amounts of energy lost through Poiseuille flow and non-Poiseuille flow are frequency dependent, (2) the frequency dependence of absorption for each fluid-grain aggregate is unique. It is probable that for any sediment the change of absorption with frequency lies between the extremes of frequency-squared dependence and square-root-of-frequency dependence.

The absorption measurements of this dissertation provide data which fit within these relatively broad theoretical limits. The resonant technique used for the measurements provided values at two and sometimes three frequencies for individual samples. Occasionally one of the resonant modes gave a value inconsistent with other values for a particular sample, assuming an increase of absorption with frequency. Omitting such inconsistencies, the relation of absorption to frequency was examined for 65 samples. This is shown graphically in Figure 12, where, in addition to the measurements, typical curves for absorption proportional to the first and second power of frequency are given.

For the frequency range involved in the measurements the relation between absorption, α, frequency, f, and a constant, K, can be approximated by the expression $\alpha = Kf^n$. If it is assumed that this expression holds down to zero frequency, then values of n may be determined from absorption measurements at two frequencies. An individual value of n so determined carries little weight by itself because of the possibilities of experimental error. An average n for a number of samples is more meaningful. For the 65 samples used, this average n equals 1.79. The standard deviation of n is 0.98.

ACKNOWLEDGMENTS

Dr. W. J. Toulis of the Navy Electronics Laboratory was my outstanding benefactor in this study, for he developed the theory for the resonant chamber method, helped to set up the basic equipment, and offered advice and encouragement throughout the work. Dr. E. L. Hamilton of NEL encouraged this study by supporting it wherever possible and by being a diving partner in the collection of samples. Drs. R. J. Christensen, G. H. Curl, and Mr. K. V. Mackenzie of NEL provided helpful suggestions throughout the work. Others at NEL who have helped in one way or another include Mr. G. Prible and Miss M. L. Hagar who did the drafting; Mr. John Newton and Mr. Kim Igelman who made the grain-size analyses; Mr. R. F. Dill, Mr. D. G. Moore, and Mr. C. J. Shipek who assisted in sample collecting.

Particularly helpful discussions of this study were provided at various times by Professor R. W. Raitt of the Scripps Institution of Oceanography of the

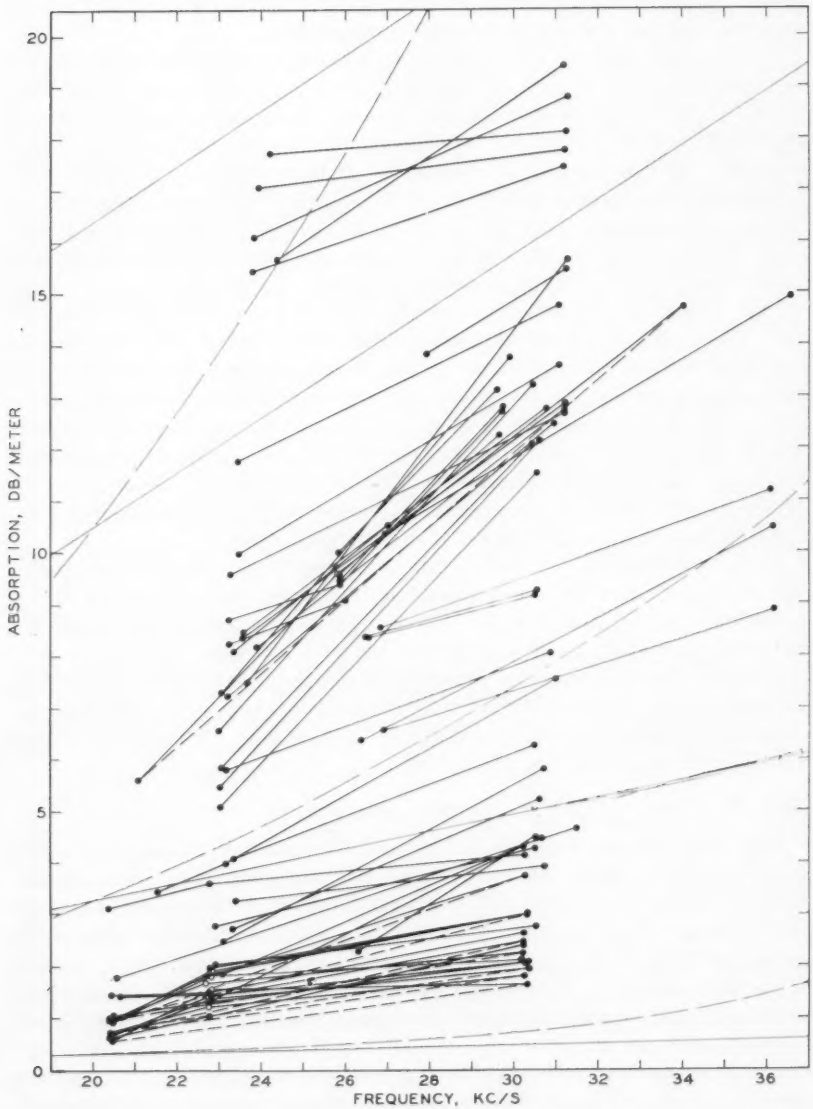

FIG. 12. Sound absorption in sediments vs. frequency.

University of California. Others at Scripps Institution who have given advice include Professors D. L. Inman, L. N. Lieberman, and H. W. Menard. Dr. R. L. Fisher, Mr. M. A. Beal, and Mr. J. H. Sherman III helped in the collection of samples.

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DISCUSSIONS AND COMMUNICATIONS

ERRATA FOR "LESSONS IN SEISMIC COMPUTING"*

Dr. R. A. GEYER†

The following errata represent the combined efforts of Messrs. William J. Zwart, John E. Owen, and Jerry Fillebrown, who gave so very generously of their time to compile this list. The Special Editor of this volume regrets that their excellent co-operation had not been made available to him at a time when it was most needed, namely, prior to the publication.

The equations in the original manuscript were expressed in the numerator-denominator form, rather than using the solidus. The decision to use the solidus was prompted by the need on the part of the Society for stringent economy measures. The adoption of this form was responsible for a marked decrease in the number of printed pages necessary to reproduce the manuscript. However, it also increased the probability of having an even higher percentage of errata than usually occurs in the first printing of a complex mathematical treatise. In an effort to minimize this, two sets of page proof were checked instead of the usual one, in addition to the galley proof.

The bulk of the errata as listed are attributable to mechanical form rather than content, and the majority of the latter, fortunately, are quite obvious to any serious student of the subject.

The Special Editor of the volume would be most appreciative if in the event additional errata are found, they be called to his attention so that they can be included in the next printing.

* Received by the Editor February 8, 1960.

† Special Editor for "Lessons in Seismic Computing."

List of Errata

Page	Line	Should Read
8	22	$1/(\Delta t/\Delta x)=\Delta x/\Delta t$
19	31	$\Delta x=1{,}000.$
20	Fig. 19	Label A, point midway between P_3 and P_4
23	26	$t=(x^2+4h^2)^{1/2}/v$
24	4	$t=(x^2+4h^2)^{1/2}/v$
25	19	$\left[(x^2+4h^2)^{1/2}/v\right]-x/v=(1/v)\left[(x^2+4h^2)^{1/2}-x\right],$
	20	$=(1/v)\left[(x^2+4h^2)^{1/2}-x\right]\left[(x^2+4h^2)^{1/2}+x\right]/\left[(x^2+4h^2)^{1/2}+x\right],$
	21	$=(1/v)\left\{4h^2/\left[(x^2+4h^2)^{1/2}+x\right]\right\}.$

(*Continued on following pages*)

Page	Line	Should Read
27	20	$h=(1/2)(v^2t^2-x^2)^{1/2}$
	31	$h=(1/2)\left[(9{,}570)^2(1.912)^2-(1{,}000)^2\right]^{1/2}$,
29	4	$h=(1/2)(v^2t^2-x^2)^{1/2}$
32	5	$x=(x_1+x_2)/2$,
	11	$t=(t_1+t_2)/2$.
34	10	v_1 as 6,000 ft/sec is the
41	35	$\sin\alpha=v(dt/dx)$,
45	13	$\overline{O'P_4}^2=\overline{OP_4}^2+\overline{OO'}^2-(2\overline{OP_4})(\overline{OO'})\cos\measuredangle P_4OO'$.
	33	$\sin\measuredangle OP_4O'=9{,}962\ (\sin 95°)/11{,}054$,
	34	$=9{,}962\ (0.9962)/11{,}054$,
48	26	$\cos\measuredangle O'OP=-\sin\phi$.
50	2	$(vt)^2=(2H)^2+x^2\pm 2(2H)x\sin\phi$,
52	22	$(dt/dx)_{x_c}=-\cos 2\phi/v$.
54	21	$(1/2)(1.332+1.353)=1.342$ sec.
55	2	$(1/2)(1.377+1.420)=1.398$ sec.
56	2	$O_1'P=12{,}800$ ft,
	23	$O_2'P=9{,}600$ ft,
61	12	$\sin\alpha/\cos\alpha=\tan\alpha$,
	16	$\tan\phi=(1/2)(\tan\alpha-\tan\alpha')$.
86	7	$x_c=2h_1(v_1/v_2)/\left[1-(v_1/v_2)^2\right]^{1/2}$,
	15	$t_c=(1/v_1)\left[4h_1^2v_1^2/(v_2^2-v_1^2)+4h_1^2\right]^{1/2}$,
	16	$=(1/v_1)\left[4h_1^2v_2^2/(v_2^2-v_1^2)\right]^{1/2}$,
102	18	$a=\left[(7{,}500)(1.621)-10{,}000\right]/2(7{,}500/5{,}750-5{,}750/7{,}500)$,
	19	$\cong(12{,}160-10{,}000)/2(1.304-0.767)$,
108	Fig. 65	Slope ${}_oV_2$ instead of ${}_oV_1$
113	5	$\delta=(\beta-\alpha)/2=(59°30'-53°50')/2$,
116	10	$=\sin(\phi+\delta)/v_1$.
	36	$=(2h_0/v_1\cos\alpha)(\cos\delta-\sin\phi\sin\alpha)$,
	37	$=\left[2h_0/v_1\cos(\phi+\delta)\right]\left[\cos\delta-\sin\phi\sin(\phi+\delta)\right]$,
	38	$=\left[2h_0/v_1\cos(\phi+\delta)\right](\cos\delta-\sin^2\phi\cos\delta-\sin\phi\cos\phi\sin\delta)$,
117	2	$=\left[2h_0/v_1\cos(\phi+\delta)\right](\cos^2\phi\cos\delta-\sin\phi\cos\phi\sin\delta)$,
	3	$=\left[2h_0\cos\phi/v_1\cos(\phi+\delta)\right]\left[\cos(\phi+\delta)\right]$,
122	36	$t_{ST}=t_{AB}-\left[(h_a+h_b)/v+t_b\right]$,
	40	$t_{TS}=t_{AB}-\left[(h_a+h_b)/v+t_a\right]$
138	31	$\cos\psi\cos^2\delta/(\cos^2\psi\cos^2\delta+\sin^2\psi)^{1/2}$,
		$\sin\psi/(\cos^2\psi\cos^2\delta+\sin^2\psi)^{1/2}$,
		$\cos\psi\sin\delta\cos\delta/(\cos^2\psi\cos^2\delta+\sin^2\psi)^{1/2}$
142	19	$(1/\Delta\sigma)^2\cong(1/\Delta x)^2+(1/\Delta y)^2$.
150	12	$\Delta t/\Delta x=(t_2-t_1)/(x_2-x_1)$.
160	12	$\sin\delta=(v^2t_O/2h\cos\psi_{12})\left[(\Delta t)_{12}/2\rho\right]$.
165	2	P_1Q_1
167	34	$\sin\phi_{12}=v_1^2t_0(\Delta t)_{12}/2h_0\Delta x$.

Page	Line	Should Read
	37	$\sin \phi_{34} = v_1^2 t_0 (\Delta t)_{34} / 2h_0 \Delta x$,
177	Fig. 91	line $S_1' S_1$
179	31	$p = \sin \alpha / v_1$.
185	14	$x = 2\left[h_1 p v_1 / (1 - p^2 v_1^2)^{1/2} + h_2 p v_2 / (1 - p^2 v_2^2)^{1/2}\right]$,
	15	$t = 2\left[h_1 / v_1 (1 - p^2 v_1^2)^{1/2} + h_2 / v_2 (1 - p^2 v_2^2)^{1/2}\right]$.
187	13	running
188	12	$-1/v_i < p < 1/v_i$,
190	2	in equations (3), p. 182, by $-p$
207	17	$t = (-1/a)\left[\log \left\{(1/S)\left[1 + (1 - S^2)^{1/2}\right]\right\}\right]_{pv_0}^{pv}$.*
	21	$t = (1/a) \log \left\{\left[1 + (1 - p^2 v_0^2)^{1/2}\right] pv / \left[1 + (1 - p^2 v^2)^{1/2}\right] pv_0\right\}$.
208	3	$t = (1/a) \log \left[(v_0 + ah)\left[1 + (1 - p^2 v_0^2)^{1/2}\right] / v_0\left\{1 + \left[1 - p^2 (v_0 + ah)^2\right]^{1/2}\right\}\right]$.
213	13	$h_{\max} = (v_0/a)(1 - \sin \alpha_0)/\sin \alpha_0$
	16	page 207
	25	$x_L = (1/ap)\left[-(1 - S^2)^{1/2}\right]_{pv_0}^{1} = (1/ap)(1 - p^2 v_0^2)^{1/2} = (v_0/a)\cot \alpha_0$
	27	$t_L = (-1/a)\left[\log \left\{(1/S)\left[1 + (1 - S^2)^{1/2}\right]\right\}\right]_{pv_0}^{1}$,
	28	$= (1/a) \log \left\{(1/pv_0)\left[1 + (1 - p^2 v_0^2)^{1/2}\right]\right\}$,
	29	$= (1/a) \cosh^{-1} (1/pv_0)$.*
214	15	$\left[(v_0/a) \cot \alpha_0, -v_0/a\right]$.
	21	$\left[(v_0/a) \cot \alpha_0, (v_0/a)(1 - \sin \alpha_0)/\sin \alpha_0\right]$,
217	12	$(y^2 - 1)^{1/2} = (e^x - e^{-x})/2$.
	20	$x = \log \left\{(1/z)\left[1 + (1 - z^2)^{1/2}\right]\right\}$.
	24	$\cosh^{-1} (1/z) = \log \left\{(1/z)\left[1 + (1 - z^2)^{1/2}\right]\right\}$.
218	15	$C: \left[(v_0/a) \cot \alpha_0, -v_0/a\right]$
	17	$R = v_0/a \sin \alpha_0$.
	21	$= (v_0/a)\left[(1 - \sin \alpha_0)/\sin \alpha_0\right] = R(1 - \sin \alpha_0)$.
	26	$t_{OP} = (2/a) \cosh^{-1} (1/\sin \alpha_0)$;
	28	$t = (2/a) \sinh^{-1} (ax/2v_0)$.
220	25	$dt/dx = 1/v_0 \cosh (at/2)$.
221	28	$p = 1/(v_0 + ah_{\max})$.
	36	curve
222	11	$25{,}000 = 2\ (6{,}000/0.6) \cot \alpha_0$,
	30	$v = 6{,}000 + (0.6)(6{,}000)$,
	Table II	
226	Col. 4	$\sinh (1.3025a)$
	35	$t = (2/0.485) \sinh^{-1} \left[(0.485x)/2(5{,}750)\right]$,
227	16	2. $0.485x/2(5.750) = 0.04217x/1{,}000$,
	18	4. $t = (2/0.485) \sinh^{-1} \left[(0.485x)/2(5{,}750)\right]$,
	19	$= 4.124 \sinh^{-1} (0.04217x/1{,}000)$.
228	15	$\sinh (0.6820a) = 4{,}000a/v_0$
234	Last	$x = (1/ap)\left\{\left[1 - p^2 v_0^2\right]^{1/2} \mp \left[1 - p^2 (v_0 + ah)^2\right]^{1/2}\right\}$

Page	Line	Should Read
235	17	$x_C=(1/\bar{x})\left[(\bar{x}^2+\bar{h}^2)/2+\bar{h}v_0/a\right]$,
236	26	$\cosh\ at=\left\{1\mp\left[1-p^2v_0^2\right]^{1/2}\left[1-p^2(v_0+ah)^2\right]^{1/2}\right\}/p^2v_0(v_0+ah)$.*
	28	$\cosh\ at\ -\ 1$
	29	$=\left[1-p^2v_0(v_0+ah)\mp\left\{\left[1-p^2v_0^2\right]\left[1-p^2(v_0+ah)^2\right]\right\}^{1/2}\right]$ $/p^2v_0(v_0+ah)$.
	31	$a^2x^2=\left[2-p^2v_0^2-p^2(v_0+ah)^2\right.$ $\left.\mp 2\left\{\left[1-p^2v_0^2\right]\left[1-p^2(v_0+ah)^2\right]\right\}^{1/2}\right]/p^2$.
237	3	$=\left[2-p^2v_0^2-p^2(v_0+ah)^2\right.$ $\left.\mp 2\left\{\left[1-p^2v_0^2\right]\left[1-p^2(v_0+ah)^2\right]\right\}^{1/2}+p^2a^2h^2\right]/p^2$,
	4	$=\left[2-2p^2v_0^2-2p^2v_0ah\right.$ $\left.\mp 2\left\{\left[1-p^2v_0^2\right]\left[1-p^2(v_0+ah)^2\right]\right\}^{1/2}\right]/p^2$,
	5	$=2\left[1-p^2v_0(v_0+ah)\right.$ $\left.\mp\left\{\left[1-p^2v_0^2\right]\left[1-p^2(v_0+ah)^2\right]\right\}^{1/2}\right]/p^2$.
237	7	$\cosh\ at\ -1=a^2(x^2+h^2)/2v_0(v_0+ah)$;
	9	$t=(1/a)\ \cosh^{-1}\ \left[1+a^2(x^2+h^2)/2v_0(v_0+ah)\right]$.
	18	$x^2+\left[h-(v_0/a)(\cosh\ aT-1)\right]^2=(v_0^2/a^2)\ \sinh^2\ aT$.
	22	$\left[0,\ (v_0/a)(\cosh\ aT-1)\right]$
	24	$(v_0/a)\ \sinh\ aT$,
239	15	$x+\left[h-(v_0/a)(\cosh\ aT-1)\right]dh/dx=0$.
	18	$dh/dx\big\vert_{\,0}=-x_0/\left[h_0-(v_0/a)(\cosh\ aT-1)\right]$.
	28	(e) $dh/dx\big\vert_{\,0}=-(x_0-k)/(h_0+v_0/a)$.
	32	$x_0(x_0-k)/(h_0+v_0/a)\left[h-(v_0/a)(\cosh\ aT-1)\right]$,
240	3	$x_0^2+\left[h_0-(v_0/a)(\cosh\ aT-1)\right]^2=(v_0^2/a^2)\ \sinh^2\ aT$,
241	15	$t=(1/a)\ \cosh^{-1}\ \left[1+a^2(d^2+h^2)/2v_0(v_0+ah)\right]$.
243	5	$h=\left[(v_0^2+a^2d^2)^{1/2}-v_0\right]/a$.
246	2	$v_0=(ah/2)\left[\left\{1+2\left[(d/h)^2+1\right]/(\cosh\ at-1)\right\}^{1/2}-1\right]$.
	24	VII $\left\{2\left[(d/h)^2+1\right]/(\cosh\ at-1)+1\right\}^{1/2}-1$
	25	$v_0=(ah/2)\left[\left\{2\left[(d/h)^2+1\right]/(\cosh\ at-1)+1\right\}^{1/2}-1\right]$
247	25	$t=(1/a)\ \cosh^{-1}\ \left[1+a^2(d^2+h^2)/2v_0(v_0+ah)\right]$
249	22	X $t=(1/a)\ \cosh^{-1}\ \left[1+a^2(d^2+h^2)/2v_0(v_0+ah)\right]$
252	3	(1) $t=(2/a)\ \log\ \left[\left\{1+\left[1-p^2v_0^2\right]^{1/2}\right\}\right.$
	4	$\left.p(v_0+aH)/\left\{1+\left[1-p^2(v_0+aH)^2\right]^{1/2}\right\}pv_0\right]$.
	16	$\cosh\ (at/2)=\left[(ax/2v_0)^2+1+(1+aH/v_0)^2\right]/2(1+aH/v_0)$.
253	13	$\alpha=\sin^{-1}\ (v_0+a\bar{H}/V)$.]
254	40	$\mathrm{OS}=(v_0/a)\left[\cosh\ (at_0/2)-1\right]$.
	42	$r=(v_0/a)\ \sinh\ (at_0/2)$
260	4	$x=0$:
261	15	$a=2(3)^{1/2}h$,
262	6	$\tan\ \theta=-\cos\ \alpha/\cos\ \beta$.

ERRATA FOR DISCUSSION OF "FREQUENCY ANALYSIS OF SEISMIC PULSES"*

BY R. L. SENGBUSH† (GEOPHYSICS v. 25, p. 322)

I want to call attention to errors in my comments on "Frequency Analysis of Seismic Pulses" that appeared in the February 1960 issue of GEOPHYSICS. Following Woodward in his book "Probability and Information Theory," I used the notation "sinc" function. By definition, sinc $\chi = (\sin \pi\chi)/\pi\chi$. This function is intimately associated with sampling theory, although the notation is not widely used. The last lines in the fourth and fifth paragraphs on page 323 should read:

> "It merely requires convolution of the discrete spectra with the function sinc $f\tau$."
>
> "They can be obtained by convolving the sampled function with the function sinc $2f_0t$."

There were other minor errors. The Greek letter, ρ, that occurs in the first two equations should be p. The sentence after the second equation should read, "These harmonics have discrete frequencies n/T, · · · ."

I suggest that in the future galley proof of letters be sent to the author in order to prevent such errors.

As is suggested, galley proof of discussions and communications will be sent to the authors in the future. Ed.

* Received by the Editor, February 18, 1960.

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DEPARTMENTS

PATENTS

O. F. Ritzmann†

ELECTRICAL PROSPECTING

U. S. No. 2,915,699. R. C. Mierendorf and C. F. Meyer. Iss. 12/1/59. App. 9/13/56. Assign. Square D Co.

Metal Detectors. A metal detector having a laminated core wound with coils energized to produce opposing fields and a pick-up coil on the core between the primary coils, the sensitivity being increased by operating with unbalanced primary circuits so that the primary fields are not in exact opposition.

U. S. No. 2,917,732. W. P. Chase, W. R. Davis, and J. E. Snyder. Iss. 12/15/59. App. 3/22/57. Assign. Librascope, Inc.

Detector for Indicating Presence of Objects. A metal detector whose detecting coil is the tank circuit of an oscillator excited by a constant-current source, the oscillator being connected to a peak detector to indicate changes in the characteristics of the coil.

U. S. No. 2,919,396. G. H. McLaughlin and H. A. Harvey. Iss. 12/29/59. App. 1/31/55. Assign. The McPhar Engineering Co. of Canada Ltd.

Apparatus for Electromagnetic Induction Surveying. An energizing source for an electromagnetic prospecting system having a tuned coil connected to a portable a-c generator through a saturable-core reactor across which is connected a second coil tuned to a harmonic so that fields of two frequencies are simultaneously produced, selection being made by tuning the pickup circuit.

U. S. No. 2,919,397. L. W. Morley. Iss. 12/29/59. App. 4/30/56. Assign. Canada.

Method and Apparatus for Inductive Prospecting. An airborne electromagnetic prospecting system using a transmitter coil on the plane and a towed array of three orthogonal receiving coils whose signals are separately squared and combined, the effect of the primary field on the receiving coils being cancelled by combining in opposition signal from a fourth pickup coil located near the transmitting coil, changes in amplitude of the secondary field being indicated.

GEOCHEMICAL PROSPECTING

U. S. No. 2,918,579. R. L. Slobod, H. F. Dunlap, and T. F. Moore. Iss. 12/22/59. App. 1/31/57. Assign. The Atlantic Refining Co.

Exploration for Petroliferous Deposits by Locating Oil or Gas Seeps. A method of geochemical exploration by boat over water-covered areas by continuously sampling the water, separating entrained gas by vacuum, and analyzing the gas for methane concentration which is correlated with location.

GRAVIMETRIC PROSPECTING

U. S. No. 2,917,300 F. N. Spiess. Iss. 12/15/59. App. 12/7/56. Assign. The Regents of the University of California.

Frequency Modulating Accelerometer. A gravity meter having a cantilever arm carrying the movable plates of three air condensers having a common fixed plate and with the condensers connected in a high frequency phase-shift oscillator circuit whose frequency changes are observed.

† Gulf Oil Corporation, Patent Department.

MAGNETIC PROSPECTING

U. S. No. 2,914,728. J. J. Brophy and J. W. Buttrey. Iss. 11/24/59. App. 10/2/56. Assign. International Business Machines Corp.

Hall Effect Probe. A magnetic measuring probe having a thin sheet of insulating material carrying a thin film of semi-conductor material in the shape of a cross with two opposite arms connected to a source of current and the other two opposite arms connected to a potentiometer.

U. S. No. 2,916,690. B. D. Leete. Iss. 12/8/59. App. 12/6/52. Assign. General Electric Co.

Apparatus for Measuring Magnetic Fields. A nuclear magnetic resonance magnetometer for weak fields having a pair of opposing magnets with air gaps so that the ambient field increases the flux in one air gap and decreases the flux in the other air gap, and measuring the frequency difference between the n.m.r. in the two air gaps.

RADIOACTIVITY PROSPECTING

U. S. No. 2,911,535. N. L. Muench. Iss. 11/3/59. App. 1/8/57. Assign. Jersey Production Research Co.

Apparatus for Pulsing a Scintillation Detector. A scintillation counter whose photomultiplier is turned on by the application of a positive gating pulse to a selected pair of dynodes and a negative pulse to another pair of dynodes, and turned off by applying pulses that produce zero potential across any pair of dynodes.

U. S. No. 2,917,729. M. C. Ferre. Iss. 12/15/59. App. 8/27/54. Assign. Schlumberger Well Surveying Corp.

Pulse Analyzer. A pulse height analyzer in which the pulse is applied to the horizontal deflecting plates of a c-r tube and the derivative of the pulse is applied to the vertical deflecting plates so as to produce a line spectrum of pulse heights, the c-r tube screen having target electrodes that are connected to separate counters.

SEISMIC PROSPECTING

U. S. No. 2,911,600. T. Bardeen. Iss. 11/3/59. App. 11/14/55. Assign. Gulf Research & Development Co.

Control for Seismograph Prospecting Filter Circuits. A circuit for independently controlling the mid-frequency and the band width of band pass filters having saturable-core inductances, the control coils for the series-tuned inductances and the control coils for the parallel-tuned inductances being respectively in adjacent arms of a Wheatstone bridge circuit, with the mid-frequency control current applied across one diagonal of the bridge and the band-width control current applied across the other diagonal of the bridge.

U. S. No. 2,912,060. W. T. Evans. Iss. 11/10/59. App. 4/19/55. Assign. Sun Oil Co.

Seismic Prospecting. An air shooting system in which detonating cord is suspended above the ground in a curved arc so that the wave front in the earth will be properly directed and curved for optimum reflection energy.

U. S. No. 2,912,164. D. O. Seevers. Iss. 11/10/59. App. 5/2/55. Assign. California Research Corp.

Seismic Record Statistical Computer. A system for identifying reflections on a multi-trace seismogram by first determining the distribution frequency of various amplitudes taken at millisecond intervals, then determining the number of amplitudes in a given category over progressive five-millisecond intervals throughout the seismogram, squaring and summing the count for all traces for each interval, and comparing with the over-all amplitude distribution.

U. S. No. 2,912,672. G. B. Loper. Iss. 11/10/59. App. 7/5/55. Assign. Socony Mobil Oil Co., Inc.

Intensity-Modulated Transient Display. A system for repeatedly reproducing an endless multitrace magnetic seismogram on a c-r tube by vertically sweeping the c-r beam on a raster whose horizontal sweep is synchronized with motion of the seismogram, and having a number of monostable multivibrators of different periods for the respective traces, the multivibrators being rendered unstable at the beginning of the vertical sweep with the unstable period being varied by the seismic impulse, triggering of the multivibrator effecting a momentary increase in the intensity of the c-r beam.

U. S. No. 2,912,673. G. M. Groenendyke. Iss. 11/10/59. App. 9/28/55. Assign. Socony Mobil Oil Co., Inc.

System for Visual Display of Transients. A system for repeatedly reproducing an endless multitrace magnetic seismogram on a c-r tube by vertically sweeping the c-r beam on a raster whose horizontal sweep is synchronized with motion of the seismogram, the trace signals being fed to comparators activated at the beginning of the vertical sweep and producing time-modulated pulses that increase the beam intensity whenever the trace signal exceeds a predetermined amplitude.

U. S. No. 2,913,701. H. Wachholz. Iss. 11/17/59. App. 7/2/58. Assign. Prakla Gesellschaft für Praktische Lägerstattenforschung G.m.b.H.

Electrodynamic Transducers for Vibrations Transmitted Through Solids. A suspended coil electromagnetic seismometer whose suspended structure has a magnet that is attracted by a fixed magnet on the case so as to compensate the effect of gravity and permit attainment of a low natural frequency.

U. S. No. 2,914,854. J. A. Westphal. Iss. 12/1/59. App. 6/20/56. Assign. Sinclair Oil & Gas Co.

Apparatus for Plotting Migrated Geologic Cross-Sections. A seismic cross-section plotter having a head for manually scanning a pair of seismograms, electrical signals representing the longitudinal position of the head and its angular orientation being fed into computers that drive servos connected to an arm carrying a plotting head.

U. S. No. 2,915,588. A. G. Bose. Iss. 12/1/59. App. 8/6/56.

Pressure Wave Generation. An electroacoustic transducer for generating a spherical wave and having a number of small closely-spaced pressure transducers mounted on a baffle in the form of a spherical sector.

U. S. No. 2,915,599. R. E. Ricketts. Iss. 12/1/59. App. 6/6/52. Assign. General Electric Co.

Logarithmic Amplifier. A sonar amplifier having a cathode follower and a cathode-driven amplifier with a common cathode impedance which includes an element with a logarithmic characteristic.

U. S. No. 2,915,738. C. B. Vogel. Iss. 12/1/59. App. 1/22/57. Assign. Shell Development Co.

Hydrophone Detector. A variable air-gap reluctance-type hydrophone having between the inner and outer chambers separated by the transducer diaphragm two parallel magnetically biased check valves to compensate for static pressure variations.

U. S. No. 2,917,706. C. D. Thompson. Iss. 12/15/59. App. 7/14/55. Assign. Phillips Petroleum Co.

Seismometer Testing Apparatus. A circuit for testing detectors either singly or in groups by means of a resistance meter and also having galvanometers for checking phasing of the detector when it is manually moved upward.

U. S. No. 2,917,918. J. E. Jenkins. Iss. 12/22/59. App. 10/3/56.

Vibration Measuring and Recording Apparatus. A self-contained vibration recorder having three

pendulums operating in mutually perpendicular planes and employing optical recording with a different color-coded light pattern for each pendulum beam.

U. S. No. 2,918,001. E. L. Alford. Iss. 12/22/59. App. 9/30/57. Assign. One-half to William W. Garber.

Radio-Proof Electric Firing Device. An electric initiator whose leg wires are connected to an r-f choke having a relay armature so that d-c firing current will actuate the relay which completes the bridge wire circuit.

U. S. No. 2,919,423. W. H. Williams and D. A. Baldwin. Iss. 12/29/59. App. 4/29/54. Assign. U.S.A.

Submarine Bottom Scanner. An acoustic water-depth indicator using a directional piezo-electric transducer that is oscillated in a plane transverse to the direction of traverse and having a c-r tube display with synchronized radial sweep and whose spot is increased in brightness when the reflection is received, so as to obtain a transverse cross-section of the bottom contour.

WELL LOGGING

U. S. No. 2,911,487. F. N. Tullos. Iss. 11/3/59. App. 12/7/55. Assign. Jersey Production Research Co.

Amplifying System. An expander amplifier for well logging or signaling having two tubes with a common anode resistor, and with the signal applied to one grid and also applied to the other grid in reversed phase.

U. S. No. 2,911,534. H. R. Brannon, Jr. and J. A. Rickard. Iss. 11/3/59. App. 4/27/56. Assign. Jersey Production Research Co.

Gamma Ray Scintillometer. A gamma-ray detector having a photomultiplier tube adjacent to a transparent medium containing a number of parallel cylindrical scintillating elements whose length is sufficient to completely absorb Compton electrons and whose radius is related to the least energy of Compton electrons, the angle of scattering, and the density of the scintillating material.

U. S. No. 2,911,536. S. A. Scherbatskoy. Iss. 11/3/59. App. 6/12/51. Assign. PGAC Development Co.

Simultaneous Neutron and Gamma Ray Well Logging System. A combined neutron logging, gamma-ray logging, and casing-collar logging device in which neutron and gamma-ray pulses are given opposite polarity so that they can be separated at the surface with the respective channels rendered inactive with the onset of a pulse of opposite polarity.

U. S. No. 2,912,495. J. Moon and R. C. Crooke. Iss. 11/10/59. App. 2/3/56.

Device for Viewing Oil Well Bore Hole. A closed-circuit television system having in the well a television camera with a lens whose axis is parallel to the borehole axis and is protected by a hydraulically operated flexible closure and with a motor-driven piston that forces clear liquid into the space between the lens and the closure.

U. S. No. 2,912,932. E. D. Ayers. Iss. 11/17/59. App. 4/4/56.

Well Treating Apparatus. A circuit for spotting well perforations with respect to a radioactivty log and having a Geiger-Müller tube connected in series with the perforator firing device so that the latter may be fired at a desired log indication by applying sufficient voltage to break down the tube.

U. S. No. 2,913,195. O. V. Phillips. Iss. 11/17/59. App. 8/1/55. Assign. The Star Recorder Corp. of Denver.

Crank for Use with Recording Apparatus for Earth Bore Drilling. A crank handle for the cable reel of a drilling rate recorder which permits adequately tensioning the line to the traveling block.

U. S. No. 2,914,677. W. R. Arnold. Iss 11/24/59. App. 3/8/54. Assign. Schlumberger Well Surveying Corp.

Well Logging Apparatus. An ion-accelerator type neutron source for use in a borehole and in which the neutron flux is monitored and used to control the accelerator so as to maintain a uniform flux.

U. S. No. 2,914,727. W. G. Price. Iss. 11/24/59. App. 4/4/57.

Method and Apparatus for Measuring Magnetic Fields. A magnetometer having an inductor coil which is rapidly rotated about an axis and simultaneously rotated at a slower rate about another axis at right angles to the first axis and the maximum signal through a complete cycle indicated.

U. S. No. 2,914,947. R. J. Stegemeier. Iss. 12/1/59. App. 12/11/56. Assign. Union Oil Co. of Calif.

Temperature Recorder. A small-diameter recording thermometer whose chart is rotated by the increasing pressure of the ambient fluid so as to record the temperature at various pressures from which the depth may be determined.

U. S. No. 2,915,696. E. S. Cornish and D. E. Stark. Iss. 12/1/59. App. 5/9/56. Assign. George E. Failing Co.

Electrical Well-Logging Apparatus. A two-terminal electric logging system in which the resistivity is measured with a constant-current ohmmeter using commutated d-c and the self-potential is obtained through a long-time constant filter connected across a capacitor in series with the well electrode.

U. S. No. 2,915,697. E. S. Cornish. Iss. 12/1/59. App. 4/11/57. Assign. George E. Failing Co.

Method and Apparatus for Electrical Logging of Bore Holes. A system for changing the potential electrode connections in an a-c electric logging circuit without using additional cable conductors by having in the sonde a rectifier across a resistor in the current circuit with the rectifier output actuating a relay that changes the connection to the potential electrodes when a high current is used.

U. S. No. 2,915,739. R. C. Rumble and H. M. Buck. Iss. 12/1/59. App. 12/7/56. Assign. Jersey Production Research Co.

Sound Monitor for Subsurface Packer. A subsurface well flowmeter having a packer inflated by a reversible electric motor controlled from the surface and a vane-type impeller that actuates a contactor to signal flow rate.

U. S. No. 2,915,830. B. G. Price. Iss. 12/8/59. App. 5/21/58. Assign. Tuboscope Co.

Tubing Caliper. A well calipering device having a circumferential array of outwardly biased feelers and a coil on a magnet that rotates to scan the position of the feelers, the amplitude of the emf generated as the magnet rotates being recorded.

U. S. No. 2,916,691. J. D. Owen. Iss. 12/8/59. App. 2/14/55. Assign. Phillips Petroleum Co.

Electrical Well Logging. A system for determining the azimuthal variation of resistivity around a borehole having an axial spherical electrode and a number of toroidal coils symmetrically placed about the electrode and measuring the emf generated in the respective coils by radial current flow from the electrode.

U. S. No. 2,917,704. J. J. Arps. Iss. 12/15/59. App. 5/24/54.

Earth Formation Logging System. A system for electrically determining the presence of a rock interface below the drill during drilling using an insulated drill bit on a drill collar having other insulated electrodes connected to a measuring system that controls an electromagnetic drilling fluid valve so that the resulting pressure variations can be detected and recorded at the surface.

U. S. No. 2,919,015. G. F. Turechek. Iss. 12/29/59. App. 8/29/55. Assign. Dresser Industries, Inc.

Wireline Feed-In Device. A device for feeding a line through a lubricator on a well under pressure and having a friction wheel that engages the cable sheave just above the lubricator, the friction wheel being driven by an endless draw chain and brought into engagement with the line on the sheave by a support lever.

(See also Patents 2,911,535 and 2,917,729 listed under Radioactivity Prospecting; and Patents 2,912,165 and 2,914,725 listed under Miscellaneous.)

MISCELLANEOUS

U. S. No. 2,911,642. T. J. Hickley, C. A. Burmister, and R. R. Ross. Iss. 11/3/59. App. 12/19/55. Assign. U.S.A.

Electronic Position Indicator. A radio position determining system in which the mobile station transmits a single frequency carrier with pulse modulation to two fixed transponder stations having known time delays and in which the delayed signal received at the mobile station is matched with the transmitted signal so as to measure the transit time to the fixed stations.

U. S. No. 2,912,165. W. L. Poland. Iss. 11/10/59. App. 5/6/55. Assign. Schlumberger Well Surveying Corp.

Computer. An electromechanical analog computer for computing formation porosity from the measured resistivities of the mud cake, mud filtrate, and formation.

U. S. No. 2,912,641. R. J. Ruble. Iss. 11/10/59. App. 7/27/56. Assign. Texaco Development Corp.

Analysis Techniques Based on Nuclear Magnetic Resonance. A system for making nuclear paramagnetic resonance measurements on a core as it is cut by the drill and in which the core passes through an n.p.r. detector head in the lower end of the drill stem and discharges into the mud stream, the apparatus also containing monitoring detector heads with known samples of material being sought so that the operator can monitor adjustment of the apparatus in the borehole.

U. S. No. 2,912,689. E. C. L. de Faymoreau. Iss. 11/10/59. App. 8/16/57. Assign. International Telephone and Telegraph Corp.

Radio Navigation System. A radio navigation beacon having a rotating directional antenna and transmitting semi-random pulses and fixed pairs of reference pulses with the receiver comparing the two sets to produce a bearing indication.

U. S. No. 2,913,170. R. G. Piety. Iss. 11/17/59. App. 7/16/54. Assign. Phillips Petroleum Co.

Electrolytic Analogue for Approximately Simulating Extensions in Space to Infinity. A potentiometric model for simulating current flow in electric logging and which employs two adjacent triangular electrolytic tanks, one tank representing the real field and the other tank representing the field obtained by cylindrical inversion with the latter including representation of infinitely distant points.

U. S. No. 2,913,658. N. T. Burdine. Iss. 11/17/59. App. 3/29/54. Assign. Socony Mobil Oil Co., Inc.

Measurement of Physical Conditions of Porous Material. A method of determining permeability of a core by measuring the intensity of nuclear magnetic resonance under fluid saturations of a liquid hydrocarbon and of liquid deuterium oxide.

U. S. No. 2,913,719. A. F. Hasbrook. Iss. 11/17/59. App. 4/9/54. Assign. Olive S. Petty.

Radiolocation Method and Apparatus. A Loran system in which an individual cycle of the pulse train is identified by increased amplitude so as to increase the precision with which pulse envelopes can be matched.

U. S. No. 2,913,897. D. Kirkham and J. E. Adams. Iss. 11/24/59. App. 9/28/56. Assign. Iowa State College Research Foundation, Inc.

Apparatus for Measuring Diffusion Coefficients of Soil in Place. A gas permeameter for soil having a tube that is driven into the ground with a water-sealed float closing its upper end, and arranged so that downward movement of the float driving air through the soil can be observed.

U. S. No. 2,914,686. R. J. Clements, R. J. Loofbourrow, and B. D. Lee. Iss. 11/24/59. App. 10/6/53. Assign. Texaco Inc.

Crystal Microphone. A microphone for an acoustic well sounding apparatus having a piezoelectric crystal mounted in contact with the bottom and sides of a cup-shaped holder and having a thin diaphragm separating the crystal from the well fluid and through which the pressure is applied to the crystal.

U. S. No. 2,914,725. D. H. Carter and O. R. Smith. Iss. 11/24/59. App. 6/4/56. Assign. Welex, Inc.

Drilling Mud Filter Cake Resistivity Measurement. A device for measuring mud filter cake resistivity by accumulating the mud cake in a filter press and embedding electrodes in the mud cake as it is being formed and subsequently making an a-c resistivity measurement by means of the embedded electrodes.

U. S. No. 2,914,862. H. E. Hendriks. Iss. 12/1/59. App. 5/28/57.

Strike-Dip Measuring Aid. A device for measuring the dip and strike of an outcrop using a Brunton compass and having a plate carrying a rotatable disk with cleats against which the Brunton is placed so that by rotating the disk the Brunton can be oriented to read the strike and dip angles.

U. S. No. 2,915,242. H.-G. Doll. Iss. 12/1/59. App. 6/2/53. Assign. Schlumberger Well Surveying Corp.

Automatic Computing Apparatus. A computing device having a light beam or c-r beam deflected according to one variable and a moving screen with opaque curves relating to a second variable, the curves being arranged so that a multivalued function will have its positive and negative values in different parts of the screen separated by a reference line so that the pulses can be separately counted and algebraically combined.

SELECTED LIST OF U. S. PATENTS
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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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Contemporary Geodesy, Geophysical Monograph No. 4, Charles Whitten and Kenneth H. Drummond, Editors, American Geophysical Union, Washington, 1959, 99. pp. $5.50.

This monograph is a record of the proceedings of a conference held at the Harvard College Observatory-Smithsonian Astrophysical Laboratory, Cambridge, Massachusetts, in December of 1958. It was attended by over one hundred scientists representing government agencies, institutions, universities, and companies. The report covers, apparently in entirety, the 15 papers and discussions which followed.

As might be expected in such a conference, much of the material consisted of definitions, historical comments, progress reports, and technical discussions of the finer points.

Subjects covered by the various papers include proposals for a geodetic network in the oceans, the bench marks consisting of arrays of submerged transponders, water distance measurements by means of Sofar, improved geodetic positioning on earth through observations on celestial bodies,

limitations of the utility of rockets for geodetic purposes, satellites and their geodetic applications, suggestions for particular forms of satellites and orbits, and computations pertaining to satellite data. It is concluded that eventually the space co-ordinates of the tracking stations might be determined to an accuracy of about 30 meters, a truly remarkable prospect.

This monograph has much to offer to the layman who desires a broad appreciation of the newer aspects of geodesy and related subjects.

To the active geodesist it would seem to be required reading.

JAMES AFFLECK
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Application of Ray Theory to the Problem of Long-Range Propagation of Explosive Sound in a Layered Liquid, C. L. Pekeris, I. M. Longman, and H. Lifson, *Bulletin of the Seismological Society of America*, Vol. 49, 1959, pp. 274–250.

A numerical investigation is made of a transient disturbance in a liquid stratum which overlies a semi-infinite liquid possessing a greater density and acoustic wave velocity. The point source of pressure has a step-function dependence on time and the pressure detector is located at a range of 460 times the thickness of the liquid layer. The effectively "exact" seismogram resulting from the numerical application of ray theory is compared with the approximate results obtained earlier using normal-mode theory. It is readily apparent that the lower frequency behavior of the exact-ray solution is closely correlated with the disturbance associated with the first normal mode.

The authors are to be congratulated on this rather unique investigation, which is the first account of the numerical application of exact-ray theory to a case involving several hundreds of rays. In view of this fact, it is worthwhile considering if the technique is routinely applicable, either immediately or in the near future, to more complex layered media. At first it would appear that the answer is no since the investigation reviewed here involved an extremely long computing time. This conclusion is, however, rather pessimistic. One or two alternative computing schemes offer prospective computing economies; also digital computers should soon become available with speeds up to a factor of a hundred greater than the WEIZAC. It is therefore this reviewer's opinion that the next few years will see the practical application of ray theory to solid media involving several tens of strata.

J. W. C. SHERWOOD
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Seismic-Reflection Representation of the Bentheimer Sandstone in the Meppen Area, Karl-Heinz Seelis, *Erdöl und Kohle*, Vol. 12, 1959, pp. 953–957 (in German).

In a well-illustrated, clearly-written paper, Dr. Seelis tells how the Bentheimer sandstone was identified, correlated across faults, and followed to pinchout entirely by seismic reflection methods.

Near Meppen on the Ems, records had normally been of average quality when produced by conventional techniques, including a 34–55 cps filter pass-band. Excessive noise prevented the use of broad-band filters. Narrow filters, however, produced characterless reflections which could not be identified with any particular objective horizon. Closely adjacent reflections merged into one after narrow filtering.

Clearly, it was necessary to remove much of the noise by means other than filtering if a broader filter response was to be usable. "Tapered" patterns were adopted as the most efficient means of eliminating noise ahead of the amplifiers. Tapered, two-dimensional shot patterns were used with non-tapered, six-seismometer groups. Shot patterns were chosen rather than seismometer patterns because the marshy ground made seismometer pattern layout difficult but afforded easy drilling for shallow holes.

Noise was thus suppressed sufficiently to permit substitution of 23–120 cps filters for the narrower 34–55 cycle filters previously required. Character was thereby sufficiently preserved to allow reflection

polarity to be determined. Since the Bentheimer sandstone has a higher velocity than that of both the subjacent and superjacent beds, the reflections from the top and bottom of that horizon were distinguished and identified by reason of their opposite polarity.

Character correlation carried the key horizon across faults. Clear onsets allowed the top and bottom Bentheimer reflections to be followed to the trace at which pinchout occurred.

Subsequent wells have completely confirmed the interpretation.

Dr. Seelis has described in this paper a new and most promising avenue for the seismic exploration of stratigraphy.

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Contribution to a Theory of the Directional Effect of Groups of Seismographs in a Case of Pulse Vibrations, I, V. S. Issayev, English Edition of *Bulletin (Izvetsiya), Academy of Sciences, USSR, Geophysics Series*, No. 6, 1958, pp. 437–443.

On the Theory of the Directional Effect of a Group of Seismometers in Case of Pulse Oscillations II, V. S. Issayev, English Edition of *Bulletin (Izvestiya), Academy of Sciences, USSR, Geophysics Series*, No. 10, 1958, pp. 719–717.

The author points out that many papers have treated the directivity of detector arrays subject to sinusoidal excitation, whereas little attention has been given the transient behavior of such arrays. After properly observing that the computation of transient behavior by Fourier synthesis would be too tedious, he sets about to compute the behavior directly in terms of assumed simple pulses.

The treatment is somewhat disappointing in its limited scope. Only two arrays are treated, one consisting of four identical detectors equally spaced along a line, and the other of two such detectors. Plane waves in a homogeneous medium are assumed. The theory consists really of the statement that the resultant signal is the sum of four (or two) identical pulses, properly delayed in time, although the author devotes more than two pages to equations indicating this addition for one assumed pulse waveform. Two waveforms are considered, one consisting of one cycle of a sine-wave and the other quite similar to it, except with onset and tail smoothed out so as to have continuous derivatives.

For each of these assumed waveforms, the resultant sum is plotted for increasing values of time delay, yielding two families of waveforms quite similar to those shown in Figure 11 of a paper by White, which appeared in the January, 1958, issue of GEOPHYSICS. These waveforms are the primary results of this analysis, and much of the two papers concerned inferences which can be drawn from them.

For instance, an increase is noted between the times for the maximum of the positive peak and the minimum of the following trough, as delay across the array increases. Twice this time is defined as an apparent period and a curve of apparent period vs time-delay results. As a second point, peak-to-peak amplitude is plotted against time delay. It is noted that whereas certain values of time delay give zero output for sinusoidal excitation, the amplitude of the pulse output simply decreases smoothly without exhibiting any critical null directions.

Part II is an application of the conclusions of Part I to the practical case of reflection prospecting. Since apparent period changes with angle of arrival, some error in reflection times could result if, for instance, an onset or a trough away from the center of symmetry is being picked. Furthermore, an effect on reflection amplitude should be expected. The author notes that neither of these factors is significant unless unusually long spreads are being used.

This paper is a timely treatment of detector arrays in a form most directly applicable to seismic prospecting, and he has made sound generalizations from the simple examples computed.

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Physics and Chemistry of the Earth, Vol. 3, edited by L. H. Ahrens, Frank Press, Kalervo Rankama, and S. K. Runcorn, Pergamon Press, New York. 1959, 464 pp., $15.00.

This is the third volume of an annual series of volumes dealing with the contributions of physics and chemistry to a study of the earth.

Chapter 1. Paleoclimates.—This chapter comes from the Berkeley campus of the University of California. It is a rather brief chapter concerned with determinations of the seas of the Cenozoic era through studies of the depositional ratios of radioisotopes.

Chapter 2. Geophysical Investigations in the Eastern Caribbean. Summary of 1955 and 1956 Cruises.—This chapter of nearly one hundred pages comes from the Rice Institute and represents the cooperative effort of personnel from the Woods Hole Oceanographic Institution, the Lamont Observatory of Columbia University, Scripps Institution of Oceanography, The Rice Institute, Harvard, Princeton, Cornell, Wisconsin, and Utah Universities, Massachusetts Institute of Technology, and the Western Electric Company. The studies consist of a large amount of seismic refraction work with reversed profiles, made on the ocean bottom of the Venezuela Basin and the Greater and Lesser Antilles chain of islands and their associated submarine trenches and folds. A great amount of detail is given including graphs of about seventy reversed profiles made in the area. Computed sections obtained from the data also are given.

Chapter 3. Continental Margins and Geosynclines: The East Coast of North America, North of Cape Hatteras.—This chapter of nearly 200 pages is likewise the result of a joint effort by a large number of workers from Woods Hole, Lehigh, Princeton, Wisconsin, and the Hudson and Lamont Laboratories of Columbia University. The chapter is based largely upon seismic refraction data obtained in the area, with structural interpretations. The report comes from Lamont Observatory.

Chapter 4. The Origin of the Elements.—This highly interesting chapter of 25 pages comes from Atomic Energy of Canada, Ltd., and is a critical discussion of various theories of stellar evolution and of various thermonuclear reactions viewed in relation to the cosmic abundance curve of Suess and Urey (*Reviews of Modern Physics*, vol. 28, pp. 53–74, 1956) and by Goldberg, Mueller, and Allen (*Astronomical Journal*, vol. 62, p. 15, 1957).

Chapter 5. Silicate Melt Systems. This chapter of 74 pages comes from the USGS Laboratories, Naval Gun Factory, Washington, D. C. The chapter does not represent original work but is the collection of various phase equilibrium diagrams obtained by numerous workers and published elsewhere, of two and three component systems of metallic oxide melts having SiO_2 as one component. The purpose of the assemblage of these data is to discuss the relationship between these synthetic melts and the mineral species occurring in nature. A good list of bibliographic references is given.

Chapter 6. The Geochemistry of Thorium and Uranium.—This chapter of 50 pages comes from the Rice Institute. This is a review paper, recounting the various relevant articles in the field. At the close of the chapter, about 200 bibliographic references are given.

Chapter 7. Geochemistry in the U.S.S.R.—For numerous reasons, the language barrier perhaps, but principally because of the tremendous number of published papers from Soviet Russia, the author of this chapter can do but a little more than list the papers by name of author, with title of the paper in English. There are over twelve hundred references so listed. The listing covers the years 1954 to date. This report comes from King's College, University of Durham, Newcastle upon Tyne, England.

Chapter 8. The Electrical Properties of the Earth's Interior.— This very well-written chapter of 23 pages describes our present knowledge of the electrical properties of the mantle and core of the earth. The assumption is made that the properties of the earth are functions of the radial distance only, except perhaps for local variations of at most a few kilometers extent. These, of course, may be neglected in examining the broad picture of the earth's Interior. The 34 references given at the close of the chapter are quite adequate. This report also comes from King's College, University of Durham, Newcastle upon Tyne, England.

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Continuous Gravity Measurements on a Surface Ship with the Graf Sea Gravimeter, J. Lamar Worzel, *Journal of Geophysical Research*, Vol. 64, 1959, pp. 1299–1315.

This paper discusses instrumentation and outlines results of continuous recordings of the Graf Sea Gravimeter on a cruise from New York through the Mediterranean Sea and return.

The meter was mounted on a stable platform on a large (18,000 ton) fin-stabilized ship to minimize horizontal and vertical acceleration corrections. The gravimeter consists of a horizontal aluminum boom supported by horizontal helical springs with strong eddy-current damping. The boom position is read by a differential photocell circuit. The wave motion causes as much as 100,000 mgal variation but this is reduced by the instrumentation to 16 mgal peak-to-peak on the record. The station reading is obtained by drawing an average line through the oscillations on the record and the accuracy is believed to be of the order of ± 5 mgal. Comparisons to previous gravity measurements made in a submarine show errors attributable to differences in navigational location.

Two examples of profiles across seamounts may be of interest to those concerned with isostasy. One seamount near Bermuda is 15 miles in diameter, 8,400 ft high, and the top is 4,500 ft beneath the ocean surface. Its gravity profile of 115 mgal relief appears normal and can be explained if the seamount has a density of 2.7. The Cruiser Seamount, near the Azores, is much larger. It is 87 miles wide, 13,000 ft high, and lies 700 ft beneath the surface. Its gravity profile has 200 mgal total relief and shows a central positive anomaly flanked on both sides by gravity minima. The minima are shown in Figure 12 to be related to a downbowing of the M-discontinuity. The reviewer believed that this may imply that the critical size of a mass requiring isostatic compensation lies between 15 and 87 miles in diameter, at least in the ocean basins.

This is an important new tool for geodetic work in the oceans. It could be used for regional work in outlining basins for petroleum exploration, especially if smaller ships prove satisfactory.

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La Habra, California

Airborne Gravity Meter—Description and Preliminary Results, H. T. Lundberg and J. H. Ratcliffe, *Mining Engineering*, Vol. 11, 1959, pp. 817–820.

This article describes the airborne gradiometer which is in a preliminary state of development. The readings are qualitatively related to the vertical gradient, dg/dz. Two masses are suspended on either side of a balance, one mass lower than the other. If the system is moved into a region of different vertical gradient, a new equilibrium position will be reached.

The damping method is unusual. The balance is alternately clamped in position and then released to oscillate about the equilibrium point. The position of the system is read by determining the capacitance between one mass and a plate.

The method of interpretation of the readings is not very clearly stated.

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Resistivity Determinations from Electric Logs, Hubert Guyod, Hubert Guyod, 1957, $20.00.

Resistivity Determination from Electric Logs by Hubert Guyod was written to outline procedures which can be used for solving true formation resistivities from apparent resistivities as recorded on the conventional electrical log. Background information necessary for the practical use of conventional resistivity curves is also included. The necessary analysis charts are included for determination of true resistivities from conventional electrical logs in a number of simple cases. The analysis charts can be used with electrical logs comprised of the 16 in and 64 in normals and the 18 ft 8 in lateral or the 16 in normal and the 10 ft and 18 ft 8 in laterals provided the conditions for the different hole and formation parameters are reasonably met. Charts are presented for single-bed and multiple-bed formations. Although the charts are primarily for non-invaded beds, a limited number of analysis charts are included for invaded beds.

Typical logs are presented for single beds (both invaded and non-invaded), multiple beds and sandwich-type alternating beds. These logs are valuable for comparison with field logs. It is necessary to study the curve shapes of the logs to determine the type of beds involved. Then, qualitative studies of beds of interest are possible. Multiple beds are the most frequently occurring situation in actual field-log interpretation and an understanding of the influence of multiple beds on the log can be aided by study of curve shapes from the Guyod sample logs. The sample logs are not applicable directly to the interpretation of field logs but illustrate the response of various logging configurations opposite known formation geometries.

The Guyod analysis charts are best suited for use with lateral resistivity curves in cases where the main concern is the effect of adjacent beds on the zone of interest. However, more often than not, there are too many formation conditions for which no charts are available. It is extremely troublesome to learn all of the complications necessary to use the charts.

The advent of focussed logging devices has relegated the classical normal and lateral curves to a minor position. The value of the Guyod departure curves will, therefore, become less important in the future. Eventually, the Guyod curves will only have value in the study of old conventional logs and it is questionable just how useful they will be then.

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Electric Analogue for Resistivity Logging, Hubert Guyod, Hubert Guyod, Houston, 1958, 137 pp., $50.00.

Electric Analogue for Resistivity Logging by Hubert Guyod was prepared as a summary and analysis of work done with an electrical resistance analogue for six major oil companies. The analogue was constructed to investigate a basic electrical logging problem—to derive true formation resistivities from recorded apparent resistivities. Well-bore and formation parameters were simulated in the analogue by electrical resistances.

Formerly, departure curves were constructed mathematically. Several disadvantages were involved in this method. Charts could be made only for the simplest of conditions. Three-electrode or lateral-curve charts were made only for infinitely thick beds. The charts were not presented for easy determination of true resistivity.

This book is in two parts. The first part describes the principle of the analogue, the method for recording data, and the accuracy of results from the analogue. The second part is an investigation of the response of normal and lateral resistivity curves on single-bed and multiple-bed configurations. It discusses the shapes of normal and lateral resistivity curves under different formation conditions. Apparent resistivities, methods of analysis, and other related topics are discussed for several normal and lateral spacings.

The book is of no value for the quantitative interpretation of conventional electrical logs. It does have some value in the study of normal and lateral curve shapes for simple to moderately complex bed arrangements. However, even this use will become of only historical interest as focussed electrical logs continue to encroach on the use of conventional electrical logs.

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Analysis Charts for the Determination of True Resistivity from Electric Logs, Hubert Guyod and John A. Pranglin, Hubert Guyod, Houston, 1959, 202 pp., $22.50.

This manual presents a method for determining true resistivities from an electrical log comprised of the 16 in and 64 in normals and the 18 ft 8 in lateral. Analysis charts are included for the determination of true formation resistivity and, in some instances, the resistivity and extent of the invaded zone for single beds from 2 ft to 50 ft thick and for varying resistivities, hole sizes, and invasion diameters. The charts were constructed for a single, uniform and isotropic (invaded or non-invaded) bed

situated in a very thick uniform and isotropic formation, referred to as shale for simplification. The bed of interest has no mud cake and no low-resistivity annulus caused by filtrate invasion. Information is included for the use of the charts with non-uniform formations under certain limited conditions.

Messrs. Guyod and Pranglin devote considerable space to the resolving power of resistivity curves using their method and to the effects of inaccuracies on the various pertinent factors of apparent resistivity, mud resistivity, shale or adjacent bed resistivity, bed thickness, and hole diameter. These discussions are necessary to enlarge the usefulness of the Guyod-Pranglin charts but at the same time they help point out the limitations inherent in normal and lateral resistivity curves. The application of more complex departure curves to overcome these limitations seems useless.

Although this book is a supplement to *Resistivity Determination from Electric Logs*, it suffers from the same limitations. In actual practice, the analysis charts are not easy to use for log interpretation and they often result in no solution or a range of answers since too many conditions are not covered.

Present logging trends indicate the increased use of focussed logs such as the induction log and laterolog or guard log for true resistivity determination. Conventional logs are still being run but their importance is declining. The Guyod-Pranglin departure curves will eventually only have use in the interpretation of old logs. While Messrs. Guyod and Pranglin have done a remarkably thorough job with the manual, Mr. Guyod has himself said, "This effort is really 15 years too late."

R. A. WILSON
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The Evolution of North America, Philip B. King, Princeton University Press, Princeton, New Jersey, 1959, 189 pp., $7.50.

Here is an eminently readable book which geologists will value as a review of the geology of North America and which those in related fields will find very useful as a summary of American geology and geologic principles in the light of current thought and recent data. The thorough and rigorous treatment will hold the attention of the most well-read geologist, but the non-geologist, too, will find the lucid and colorful style of Philip King interesting and understandable. The text is spiced lightly with personal and historical vignettes, but these are inserted with complete good taste and regard for context, and most readers will be left with a wish that they had appeared more frequently. Abundant and well-chosen illustrations contribute to the ease with which discussions of complex or controversial topics can be followed.

Emphasis is upon structural development of the various elements which make up the North American continent, and sedimentary rocks are discussed largely in the light of their relationships to these elements. Reading between the lines, here is a statement of the great extent to which sedimentation is at the mercy of tectonic adjustments.

Although organization of the material is roughly chronologic, beginning with the Precambrian basement and concluding with the Pleistocene orogeny of the California Coast Ranges, the primary breakdown is by major geologic provinces. Considered in turn are the Canadian Shield, the undeformed strata of the Mid-Continent, the Appalachian belt, the Gulf Coast and Caribbean areas, and the Western Cordillera including the Rocky Mountains, the Great Basin, and the Nevadan and younger ranges of the Pacific Coast states. This arrangement necessitates a flash-back technique to preserve the historical theme, but a sense of continuity has been skillfully preserved and the complex temporal interrelationships among these areas as they evolved have been made as clear as present knowledge permits.

Interspersed with these topics are considerations of fundamental geologic problems such as the origin and significance of island arcs, deep sea trenches, and geosynclines; questions concerning continental accretion, permanence of continents, and sources of sediments for marginal geosynclines; and more local problems such as the time-table for the Nevadan orogeny, the history of the great San Andreas fault in California, and the origin of basin-and-range structure. Controversial aspects of these topics are faced squarely, and evidence bearing on them is carefully summarized from all sides. The

author then has the fortitude and good grace to present his own conclusions. In his preface, King speaks of these as " . . . willful prejudices and outrageous hypotheses, some of which will not stand the test of time." Among the strongly opinionated, there may be agreement with this evaluation but the general reader can proceed with the assurance that the ideas presented bear the authority of a lifetime of geological observation and experience and probably are as sound as any that can be produced in our present state of knowledge.

Although *The Evolution of North America* is broad in scope, it is no mechanical compilation by a "library geologist." Rather, it is drawn in essence from Philip King's many years spent with hammer and hand lens coming to grips with the rocks themselves. As a result, he has dwelled at length upon those areas in which his knowledge is first hand and to some it may seem that there is undue emphasis upon such things as the southern Appalachians, the Permian Basin of West Texas, and the California Coast Ranges. Areas such as these, however, are used as type examples to illustrate fundamental concepts and the author should hardly be criticized for selecting things about which he knows the most for this purpose.

The Evolution of North America will not find use as a text or source book because it is not extensively documented and admittedly not as comprehensive as it might be. It is, however, a book about American geology which is authoritative and conceptually sound, and it should rank high as recommended reading for all concerned with the subject.

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Modern Electronic Components, G. W. A. Dummer, Philosophical Library, New York, 1959, 472 pp. $15.

The author of this volume is by no means a sciolist. He is the head of components research, development and testing at the Royal Radar Establishment, Ministry of Supply (Great Britain), and the author of several specialized books on components as well as of numerous articles in this field.

Unfortunately, the author's approach in the present book is not consistent and it is difficult to decide whether he had the specialist or the non-specialist reader in mind; or, perhaps he had hoped to appeal to both. One does not find the customary clarification in this matter in the author's introductory comments.

There is much for the lay reader in this book. The style, for the most part, is non-technical, narrative, descriptive; the text is well illustrated with drawings and photographs; the print is clear on good quality high-gloss paper.

In its 32 chapters, the book covers most of the commonly used electronic components, such as resistors, condensers, relays, switches, transformers, batteries, etc; several chapters are devoted to environmental considerations; there are also brief discussions on reliability, effects of vibration and shock, testing methods, packaging, etc.

The specialist reader may grow weary of the book's predominant emphasis on taxonomy. Technically, the best chapters are: No. 5. Fixed Resistors, 6. Variable Resistors, 7. Fixed Capacitors, and 8. Variable Capacitors. It may be of interest to note that the titles of these four chapters are identical with the titles of Dummer's four specialized books published by Pitman in 1956 and 1957.

The remaining chapters—while they contain fair bibliographies, some technical data and charts —are for the most part descriptive and far too vague for the professional designer. For example, we read on page 276: "The simplicity of the transistor circuit as a switching device makes it extremely attractive as a relay." Can a designer decide on the basis of this statement (which he certainly knew beforehand) whether to use a transistor or an electromagnetic relay in his particular design? Incidentally, with the exception of two or three other scattered sentences, this is all that the book has to say about transistors.

The many obvious omissions in the book, including vacuum tubes, transistors *per se*, metallic rectifiers, as well as the frequently perfunctory treatment of important topics, are difficult to reconcile

with the author's tumid prefatory remark: "This is the first comprehensive book of its kind to be published in the world. . . ."

This reviewer feels that the technically oriented reader will not gain appreciably by adding this volume to his library, particularly if he is already familiar with such works as K. Henney and C. Walsh, *Electronic Components Handbook*, McGraw-Hill Book Company, vol. I, 1957, vol. II, 1958, (vol. III in preparation), or even the older book: J. F. Blackburn, *Components Handbook*, M. I. T. Radiation Laboratory Series, vol. 17, McGraw-Hill, 1948.

On the other hand, the present book may have some appeal to those laymen, in and out of the field of electronics, who have a genuine curiosity about electronic components and who are, furthermore, undeterred by the serious barrier of the $15 price.

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PUBLICATIONS RECEIVED

BOOKS

Introduction to Geophysical Prospecting, Milton B. Dobrin, McGraw-Hill Book Company, New York, $9.50.

Alaska, U.S.A., Herb and Miriam Hilscher, Little, Brown, Boston, $4.50.

The Sea Off Southern California, K. O. Emery, John Wiley and Sons, Inc., New York, $12.50.

Subsurface Mapping, Margaret S. Bishop, John Wiley and Sons, Inc., New York, $5.75.

Mineral Equilibrium, Robert M. Garrels, Harper & Brothers, New York, $6.00.

Stratigraphic Principles and Practices, J. Marvin Weller, Harper & Brothers, New York, $10.00.

Nuclear Power Plant, E. Openshaw Taylor, Philosophical Library Inc., New York, $7.50.

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Wave Propagation and Group Velocity, Leon Brillouin, Academic Press, New York, $6.00.

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MEMORIAL

BELA HUBBARD

DR. BELA HUBBARD, a natural scientist, died in Tucson, Arizona, on November 4, 1959 after recurrent heart trouble. His many friends throughout the world were shocked and saddened by his sudden death.

Dr. Bela Hubbard was born August 10, 1890 in Detroit, Michigan into one of the oldest and most respected of the colonial families of America. His first trip to Tucson was in 1897, when he was seven years old. He spent the winter with his parents at a desert camp at the site of the old Fort Lowell Ruins, which are less than a mile from the hospital where he died 62 years later.

His father, Henry Guernsey Hubbard, graduated from Harvard in 1873 and became an entomologist for the United States Government; his books in the field of entomology are still well known among students. Henry Guernsey Hubbard traveled abroad searching the world for plants which might be useful to the American economy. He achieved a wide reputation as a practical horticulturist and as a scientific investigator in the economics of orange culture.

His grandfather, also Bela Hubbard, graduated from Hamilton College in 1834. In 1837 he was appointed assistant geologist on the Michigan Geological Survey and was one of the organizers of the American Association of Geologists and Naturalists, the forerunner of the present American Association for the Advancement of Science. In 1953 the Detroit Library Commission recognized this Bela Hubbard as "one of the important educational and scientific figures in Michigan history." An old newspaper states, "Before the establishment of the United States Weather Bureau in 1873, the Hon. Bela Hubbard of Detroit began to do something about the weather and he did it in a scientific and systematic way. During the period between 1835 and 1886 he kept a record of the temperature, atmospheric pressure, the daily precipitation, wind directions, the levels of the lakes, and even the occurrences of sun spots."

Bela first attended the Michigan School of Mines and later Wisconsin University, where he specialized in mathematics and astronomy. Here, during the school year 1913–1914, he and C. W. (Tommy) Tomlinson built up a lasting friendship through the hours they spent together at the Washburn Observatory as the only two advanced students in astronomy.

His undergraduate work was completed at Columbia University in 1914 with a B.S. degree. He was granted a Masters degree from the same institution in 1916. In the summer of that year, he did field work in Puerto Rico and the Virgin Islands for his Ph.D. thesis, which dealt with Tertiary fossils of the Antillean region. This was among the first studies to show the presence of Miocene sediments on Puerto Rico. In 1917, he worked for the Topographical Section of the U.S.G.S.

There is no doubt that this mature attitude and fine scientific approach to all problems were enhanced by his close association with Amadeus Grabeau, James Ferman Kemp, Douglas Johnson, and Charles Berkey, his professors at Columbia University. He served as an instructor in the Paleontological and Stratigraphic Departments between 1915 and 1917.

His graduate work was interrupted by World War I, when he went overseas as a Lieutenant in the 29th Engineers. He was at the front for more than six months and was with the army until the end of the war. He continued his studies at a French University before returning to the U. S. After returning, and while he was completing his dissertation, he was employed at Queen's University, Toronto, Canada as an instructor. He was granted his Ph.D. degree from Columbia in 1922.

While still at Queen's University, he accepted summer employment with The Carter Oil Company of Tulsa, Oklahoma, and did geological work along the Rocky Mountain front in New Mexico in 1920. His work and methods were so outstanding that Murray Neumann selected him to explore northeast Peru late in 1920 for Standard Oil Company (New Jersey). Although commercial production had been discovered in Argentina, Peru, Trinidad, and Colombia early in the turn of the century, only a relatively small part of what now constitutes the

oil producing area of the continent had been examined for oil possibilities. The U. S. government and American oil companies, somewhat frightened by the published estimates of domestic reserves, began seriously to consider the potentialities of foreign countries, especially South America. Hubbard saw the opportunity for rugged pioneering in geology, with the prospect of attaining results that could help to alleviate a critical national situation.

Field conditions abroad in the 20's were arduous. Transportation in the remote areas was almost entirely on mule-back. Equipment was frugal. Local field assistants were untrained, usually physically weak owing to malnutrition and malaria, and the difficulties of foreign languages added to severe working conditions. It took patience and determination, along with geological inquisitiveness, to ferret out the potentialities of the difficult wilderness areas which the early geologists studied. Bela Hubbard possessed all these qualities. He exposed himself to adverse climatic conditions without regard to his own comfort and health. He drove himself relentlessly in the field, and after a most difficult day he would spend the remaining waking hours compiling notes and discussing field problems. He was indeed an ardent explorer who contributed much of the background of later geological work which lead to substantial oil discoveries in the countries he visited.

He first did reconnaissance in the Central Andes of Peru. His associates were impressed with his ability to do geology in the field under all conditions. M. A. Dresser recalls, "My most vivid recollection of Dr. Hubbard is a picture of him stalking off across country, under a broad felt hat, his pipe smoking like a chimney, while Gilbert Moore and I panted along in his wake trying to keep within sight of him—at an elevation of fifteen thousand feet."

From the high sierra country of Peru, Bela and his assistant, Gilbert Moore, surveyed their way down Rio Hullaga and later made extensive surveys along the Rio Santiago. Dr. Hubbard used novel methods to map this huge uncharted area of streams and jungle. His previous experience in astronomy served him in good stead and he succeeded in getting data and penetrating hostile country where others had failed. Experiences on "balsa" rafts traversing rapids (malpasos) on the swift streams point to the hazardous nature of this pioneering work. In the Santiago area, the geologists had interesting experiences with the Jivaro Head-shrinking Indians who were still savage at that time. On one occasion, Bela wished to visit a tribe of head-hunting Indians in the Rio Colorado country. With an interpreter, and an aged Indian guide, he approached a settlement which seemed deserted. Their only protection was a long spear carried by the old Indian and that seemed sufficient until suddenly another very old Indian appeared carrying an equally long spear. Immediately the two old men faced each other like fighting cocks, shaking their spears and jumping up and down in the dust while shouting at each other. Hubbard feared imminent bloodshed until his interpreter told him they were merely saluting each other.

Later, the party tried for months to explore the upper part of Rio Ucayali and

Rio Pachitea but were unable to do so because of the current revolution of eastern Peru against the Lima government. During one of their attempts to break through the military patrols, they surveyed six hundred miles of Rio Ucayali, by taking tours of two hours each on the river steamer. During the revolutionary period, Hubbard did succeed in mapping an extensive seepage area at Ollanta, 36 km southeast of Contamana. The party was placed under house arrest in Iquitos, but, on November 17, 1921, they escaped at midnight by chartered launch to the Brazilian frontier at Leticia, pursued by a revolutionist "gun boat."

Hubbard arrived in Buenos Aires in December, 1921, and completed the reports on his Peruvian work. In Argentina, he did geological and torsion balance work in Salta and Neuquen. About the middle of 1922, he was transferred to New York by Jersey Standard. On the ship voyage up, he met a charming young lady, Miss Florence Flynn, whom he married on August 16, 1922. Their only child, a son, Thomas Hill, was born in 1925.

The Hubbards moved to Venezuela the latter part of 1922, where he remained until 1930. He was chief geologist and later chief geophysicist of Standard Oil Company of Venezuela and Creole Petroleum Corporation. Again, he did real pioneer work. Early in 1923, a question arose concerning the location of certain boundaries near the Perija Mountains, west of Maracaibo. Hubbard's survey party was organized and, during the course of the survey, the party was attacked by the hostile and savage Motilone Indians; their escape route was sealed off. The story of their rescue reads like fiction! The manager in Maracaibo, Frank A. Dalburg, claimed he had a dream that the survey party had been wiped out by the Motilones. At any rate, he dispatched a rescue party, consisting of a 6-ft Texan named Durbin (an ex-Texas ranger) and about fifteen Venezuelans, all well equipped with arms. They contacted the survey party just as it was under heavy siege.

His knowledge of the regional geology became outstanding and after field training in geophysical methods, he used these additional methods to help locate prospective structures. He was largely responsible for the surveying of many of the basin areas of Venezuela with the torsion balance. The excellent correlation between gravity anomalies and geological structures, which he observed, gave him a life-long interest in gravity methods, and led him to urge the Jersey companies to carry on research on gravity instrumentation and interpretation. While in Venezuela, he also employed magnetic and refraction seismic methods. Although most of his later work was in geophysics, his approach to geophysics was that of a geologist rather than a physicist and he was ahead of his times in his geological interpretation of geophysical data. He was always interested in all methods of exploration and when geochemistry was introduced as a surface prospecting tool, it found support in Dr. Hubbard. When soil gas analysis was being extensively tested, Bela urged strongly that there should be some means of distinguishing between the recent and the ancient hydrocarbons even though most of his colleagues thought this was impossible.

From 1930 to 1935, he was geologist and geophysicist for The Carter Oil Company in Tulsa, Oklahoma, where he was largely responsible for instituting reflection seismic surveys by that company. In 1936, he moved to the New York office of Standard Oil Company (New Jersey) as assistant chief geologist and chief geophysicist until 1947. Here, he became acquainted with exploration on a worldwide basis and made many trips abroad. One of his trips was to Mexico, where his associates were developing a unique application of electrical restivity methods to locate faults and fracture zones in the Ebano District. He gave his enthusiastic support to this program and made a number of constructive suggestions for improvement in field and interpretation methods. Other places visited and where he was familiar with the geophysics and geology were Trinidad, Colombia, Ecuador, England, Italy, Austria, Hungary, Jugoslavia, Romania, Czechoslovakia, Poland, Germany, and Egypt.

During 1947, he moved to Tucson, Arizona, but continued active service with the Jersey Company until his early retirement in 1950. He continued consulting work for Jersey and carried on a wide range of studies on his own. An outstanding research study pertained to the crystallographic analysis of waxes produced by biological processes. He noted the alternating abundance of waxes of odd and even carbon numbers and felt this distribution was significant. Years later, Meinschein and his co-workers demonstrated that of the hydrocarbons in recent sediments, those with an odd number of carbon atoms are more abundant. His work on waxes was done at home. When he needed a more intense knowledge of chemistry, he studied chemistry, and when he needed apparatus, he made it. His microscopic pictures of waxes are without equal.

During his residence in Tucson, Bela became interested in the water supply problems of the area. He maintained very accurate weather data, and measured the rise and fall of the water level in his water well. From his studies, he concluded that the local water supply was a serious problem and that if the population continued to expand, the water supply would not be ample.

During retirement, his interests were broad and he was alert to the political and economic problems that confronted the country. His book, "The Political and Economic Structure," portrays his depth of scholarship; practically every type of government is described in this treatise. He predicted that inflation would go on unabated and that the politicians would talk of curbing it but would not do anything.

In Tucson, he also became active in a number of conservative political organizations. He was one of the founders and the first President of Education Information, Inc., which concerns itself to a considerable extent with the policies of American public schools. He was a member of the policy board of Liberty Lobby, and, in addition, active in the organizations for America and Liberty and Property, Inc. The latter organization, in 1959, published his booklet entitled "The Hybrid Race," which warns against the dangers of Americans being "brain washed" as to the dangers of race mixing.

His hobbies were photography, including microscopic and astronomical, making various objects of cut and polished stone in his well-equipped basement lapidary, and collecting old, rare editions of literary classics. He was particularly fond of fine leather and most of his rare editions had been rebound. Bela spent much pleasurable time in continuing his study of astronomy and built a fine observatory with a movable dome at his home in Tucson. His little observatory was a center of interest for some students at the University of Arizona, as well as many youngsters in the public schools.

Bela Hubbard became a member of the Society of Exploration Geophycicists in 1930 and was Secretary-Treasurer in 1934–1935. Further he was a member of The American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, American Geophysical Union, Mineralogical Society of America, Society of Military Engineers, American Association for the Advancement of Science, the Society of the Sigma Xi, The Geological Society of America, the American Geographical Society, the New York Academy of Sciences and the Paleontological Society.

Bela Hubbard is survived by his wife, Florence Flynn Hubbard, and his son, Thomas Hill Hubbard, his sister, Mrs. Alice H. Carpenter, of Oracle, Arizona, and a brother, Henry Gurnsey Hubbard, of Quartzite, Arizona.

The same thread of enthusiasm runs through the comments of all his friends. To name only a few men, unanimous in their rating of him, are Ludwig Blau, T. V. Moore, Murray Neumann, Glenn Hawkins, Wallace Pratt, D. C. Skeels, W. G. Argabrite, Dave Carlton. He was a first-rate scholar of outstanding intellectual honesty, with wide interests based upon a firm grasp of facts in many fields; he was also a generous, warm and sympathetic friend. We, who knew him, will miss him very much.

G. M KNEBEL

CONTRIBUTORS

R. J. BROD

R. J. BROD graduated from the University of Texas in 1956 with a B.S. in geology. He has field experience in geology and gravity surveying. For the past two years he has been primarily engaged in aeromagnetic interpretation. Mr. Brod is employed by the Gravity Meter Exploration Company of Houston, Texas.

JOHN W. MILES

JOHN W. MILES attended the California Institute of Technology where he received B.S., M.S., A.E., and Ph.D. degrees. In 1945 he joined U.C.L.A. as an Assistant Professor. He studied at the University of New Zealand in 1951 and at the University of London for a period in 1952.

Mr. Miles is presently a Professor in the Department of Engineering at U.C.L.A. and is a Consultant for Space Technology Laboratories.

JACK W. PETERS

JACK W. PETERS received the degree of Geological Engineer in Geophysics from the Colorado School of Mines in 1938. From 1938 to 1953 he was engaged in gravity and magnetic exploration for the Magnolia Petroleum Company. From 1953 to 1960 he was Regional Geophysicist for Mobil Producing Company and presently is Staff Geophysicist for Mobil Oil Company.

He served as 1st Vice-President of the Montana Geophysical Society in 1956 and as President in 1957.

His professional affiliations are Society of Exploration Geophysicists, American Geophysical Union, Montana Geophysical Society, Billings Geological Society, Tau Beta Pi and Sigma Gamma Epsilon.

TERRY W. SPENCER received the B.A. degree with highest honors in physics at the University of California at Los Angeles in 1951. He began graduate work in physics at the Massachusetts Institute of Technology where he served as a teaching assistant. In 1952 he was awarded the Lane Wells Fellowship in geophysics at the California Institute of Technology, which he held for three years. In 1956 he received the Ph.D. degree in geophysics for studies in elastic wave propagation. Since that time he has been associated with the California Research Corporation where he has been engaged in basic studies in theoretical seismology.

On a part time basis, he has participated in the University of California Extension Program as a lecturer in physics and mathematics.

Mr. Spencer is a member of the Society of Exploration Geophysicists, Phi Beta Kappa, and the Society of Sigma Xi.

TERRY W. SPENCER

JAMES R. WAIT

JAMES R. WAIT was born in Ottawa, Canada. He received the B.A.S. and M.A.S. degrees in engineering physics from the University of Toronto in 1948 and 1949 respectively. At this time he was employed as a junior research engineer at the Hydro Electric Power Commission of Ontario. Returning for further graduate work to the University of Toronto, he obtained the Ph.D. degree in electromagnetic theory in 1951.

From 1949 to 1952 Dr. Wait was associated with Newmont Exploration Limited of Jerome, Arizona where he conducted theoretical and experimental research in electrical prospecting. From 1952 to 1955 he was a section leader in the Defence Research Telecommunications Establishment in Ottawa where he was mainly concerned with theoretical problems in radiation. He has been associated briefly with McGill University during 1954 and Colorado University in 1955 and 1957 where he taught graduate courses in antennas and propagation. At present he is a Consultant to the Director, National Bureau of Standards, Boulder, Colorado.

Dr. Wait is a member of the Canadian Association of Physicists, the Society of Exploration Geophysicists, U.S.A. Commissions III and VI of URSI, IRE Wave Prop. Comm. and is a past president of the Boulder Chapter of RESA.

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows: Roland G. Henderson, v. 20, p. 354; George Shumway, v. 23, p. 600; J. E. White, v. 25, p. 357.

SOCIETY ROUND TABLE

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W. A. HEISKANEN ('60)

LOCAL SECTIONS

Ark-La-Tex Geophysical Society (6), Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

Canadian Society of Exploration Geophysicists (9), Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
Dr. M. B. Dobrin, *pres.*
P. J. Savage, *vice-pres.*
J. J. Hamilton, *secty.*, Canadian Society of Exploration Geoph., Shell Oil Co. of Canada, Ltd., P.O. Box 880, Calgary, Alta., Canada.
J. G. Goodwin, *treas.*

Casper Geophysical Society (11), Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

Coastal Bend Geophysical Society (24), Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

Cochabamba Geophysical Society (23), Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
R. H. Matthews, *pres.*
Charles W. Hyatt, *v-pres.*
Noel C. Manning, *secty.-treas.*, Geophysical Service Inc., Casilla #1437, Cochabamba, Bolivia.

Dallas Geophysical Society (4), Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

Denver Geophysical Society (8)
Meetings: Monthly, 1st Monday, 5:30 P.M., dinner at 7:00 P.M. ($3.00), Petroleum Club, Denver.
John C. Hollister, *pres.*
Arthur W. Black, *v.-pres.*
Charles E. McMunn, *secty-treas.* Tower Exploration Inc., P.O. Box 156, Englewood, Colorado.

Geophysical Society of Edmonton (22), Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

Fort Worth Geophysical Society (5)
O. A. Strange, *pres.*
R. H. Dana, *v.-pres.*
U. A. Rowe, *secty.*
C. H. Thurber, *treas.*, Champlin Oil and Refining Co., Box 9365, Forth Worth, Texas.

Four Corners Geophysical Society (19), Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

Geophysical Society of Houston (2), Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

Jackson Geophysical Society (15)
Joel Macgregor, *pres.*
John Babb, *v-pres.*
Thomas Tillman, *secty.-treas.*, Sun Oil Co., P.O. Box 850, Jackson, Miss.

Montana Geophysical Society (14), Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
W. H. Dawson, *pres.*
Phil Hendrick, *1st v-pres.*
F. J. Felice, *2nd v-pres.*
Max Judy, *secty.-treas.*, Sun Oil Co., Box 1896, Billings, Mont.

New Mexico Geophysical Society (18), Roswell, N. M., chartered September 18, 1957, officers elected in May.
R. E. Lawson, *pres.*
Delmer M. Woods, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
R. W. Aldrich, *secty.-treas.*, Mobile Oil Co., 714 Petroleum Bldg., Roswell, N.M.

Geophysical Society of Oklahoma City (10), Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

Pacific Coast Section (3), luncheon ($2.75) Rodger Young Auditorium, Los Angeles.
F. F. Lambrecht, *pres.*
Nolan A. Webb, *v-pres. S.D.*
Fred G. Knight, *v-pres. N. D.*
Tom Slaven, *secty.-treas.*, Western Geophysical Co. of America, 523 W. 6th St., Los Angeles, Calif.

Permian Basin Geophysical Society (7), Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
J. E. Clark, *pres.*
E. E. Fickenger, *1st v-pres.*
B. H. Hinton, *2nd v-pres.*
S. T. Miller, *treas.*
L. M. Scofield, *secty.*, Burton Exploration Co. Inc., 4513 W. Storey, Midland, Texas.

Regina Geophysical Society (22)
A. C. Armstrong, *pres.*
M. MacIver, *v-pres.*
J. R. Muir, *secty.-treas.*, The California Standard Co., 1836 Smith St., Regina, Saskatchewan, Canada.

Geophysical Society of South Texas
J. W. E. Edmonson, *pres.*
P. J. Rudolph, *v-pres.*
Donald W. Jones, *secty.-treas.*, Sun Oil Co., 832 Milam Bldg., San Antonio, Texas.

Southeastern Geophysical Society (13), New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($1.50), St. Charles Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty.-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

Southwest Louisiana Geophysical Society (16), Lafayette, La., chartered January 4, 1956, officers elected in December.
Jack Wallner, *pres.*
Walter Hurt, *1st v-pres.*
Richard Hollenbaugh, *2nd v-pres.*
Ned Pratt, *treas.*
Lucius Geer, *secty.*, Union Oil of California, Box 1224 OCS, Lafayette, La.

Geophysical Society of Tulsa (1)
Tulsa, Okla., chartered February 2, 1948, officers elected in May.
T. S. Green, *pres.*
J. E. Hawkins, *1st v-pres.*
K. S. Cressman, *2nd v-pres.*
B. L. Bass, *secty.*, Geophysical Society of Tulsa, Texaco, Inc., P.O. Box 2420, Tulsa, Okla.
Robert B. Fisher, *treas.*

Utah Geophysical Society (17)
L. D. Oster, *pres.*
K. L. Cook, *1st v-pres.*
H. H. Nuttli, *2nd v-pres.*
D. J. O'Halloran, *secty.-treas.*, Standard Oil of California, P.O. Box 1076, Salt Lake City, Utah.

Asociacion Venezolana de Geofisica (20), Caracas, Venezuela, chartered January 5, 1959, officers elected in March.
E. J. Assiter, *pres.*
D. W. Danz, *1st v-pres.*
Gunther Fiedler, *2nd v-pres.*
Manuel Zegarra, *secty.*, Asociacion Venezolana de Geofisica, Phillips Petroleum Co., Apartado 1031, Caracas, Venezuela.
C. O. Hill, *treas.*

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado.
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois.
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology.

SEG Houston Student Section
Billie Gail Dopslauf, *secty.* 2121 Hollister, Houston, Texas

University of Toronto Geophysical Society
B. R. Krause, *secty.* 502 Gilbert Ave., Apt. 107, Toronto, Ont., Canada

University of Tulsa Student Geophysical Society
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma.
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
El Paso, Texas

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced.

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah.
Meetings: Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced.

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas.

SOCIETY AFFILIATIONS

American Association for the Advancement of Science

SEG is affiliated under Section E, Geology and Geography
1515 Massachusetts Avenue
Washington 5, D. C.
Paul E. Klopsteg, *President*
Paul A. Scherer, *Treasurer*
Dael Wolfle, *Executive Officer*

The American Association of Petroleum Geologists

A Cooperative relationship
Box 979
Tulsa 1, Oklahoma
L. G. Weeks, *President*
A. H. Bell, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
G. E. Murray, *Editor*
G. S. Buchanan, *Past President*
R. H. Dott, *Executive Director*

European Association of Exploration Geophysicists

Mutually affiliated
30, Carel Van Bylandtlaan
The Hague, Netherlands
J. M. Bruckshaw, *President*
V. Baranov, *Vice-President*
B. Baars, *Secretary-Treasurer*
O. Koefoed, *Editor*
L. Solaini, *Past President*

National Research Council, Division of Earth Sciences

SEG is a member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
John N. Adkins, *Chairman*
Harry H. Hess, *Past Chairman*
Edward B. Espenshade, Jr., *Chairman-Designate*
William R. Thurston, *Executive Secretary*

Petroleum Exploration Society of Libya

Mutually Affiliated
P. O. Box 900
Tripoli, Libya
R. E. Doan, *President*
P. F. Burollet, *1st Vice-President*
J. F. Rominger, *2nd Vice-President*
J. C. Wilson, *Secretary*
P. Arni, *Treasurer*
J. S. Cullison, *Director*
R. S. M. Templeton, *Director*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

J. G. Adams (J. M. Sharpe, G. E. Fritts, C. F. Wendenburg & S. B. Stewart)
Luis Aguilera (J. G. Lievano, A. Krabath, O. DeSola & C. F. Calcanto)
Lawson Seals Beatty (J. A. Smith, H. C. Kriegel & C. L. Hubbard)
Anthony R. Barringer (H. O. Seigel, D. Wagg & R. H. Pemberton)
Marvin A. Buskala (J. D. Horton, T. H. Braun, A. C. Austin & C. R. Partridge)
W. R. Chichester (T. O. Hall, C. Sappington & J. S. Spencer)
George Bromley Clark (K. L. Cook, R. A. Black, R. R. Heinrich & C. L. Wilson)
William Harry Clark (G. Rempel, R. J. Bily, J. E. Procter & R. D. Fetherstonhaven)
Dee C. Daniels (C. F. Wendenburg, John M. Sharpe, G. E. Fritts & S. B. Stewart)
C. F. Everts (R. F. Zimmerly, H. R. Renden, R. M. Treacy & R. H. Watson)
Oliver J. Gross (M. A. Knock, J. G. Jones, J. H. Harding & W. H. Van Uchelen)
Frank M. Hall (E. L. Mount, J. P. Badami & A. Hrubetz)
E. L. Hanson (L. Ramsey, D. F. Brennen, G. Castellucci & D. M. Steel)
W. E. Held (F. L. Travis, H. B. Thomason, C. E. McMunn & J. E. Spencer)
Walter Lee Kennedy (R. J. Hope, T. O. Hall, C. P. Sappington & J. S. Spencer)
Hilmer Paul Kuppers (W. M. Rust, Jr., R. R. Thompson, W. D. Mounce & C. L. Hubbard)
Horace T. Masterson (W. D. Mounce, F. J. Feagin, L. G. Howell & C. L. Hubbard)
Ross L. Miller (G. J. Birge, T. B. Portwood, I. G. Weiske & C. Machnich)
William Wallace Murray (J. W. Hammond, J. G. Jackson, R. W. Saubert & R. W. Mossman)
Buddy Pierce (W. E. McCullers, J. A. Boydston, P. M. Mackey & J. F. Rielly)
Dale H. Reed (E. R. Brownscombe, S. C. Mut, H. F. Dunlap & F. A. Collins)
Marinus Jacobus Hendrikus Roep (R. H. T. Schut, A. Baber, S. Prins & J. R. Ley)
Charles Selman (N. A. Webb, R. N. Specht, J. E. Barthelemy, Jr. & J. M. Desmond)
Roy Carl Schultz (P. S. Stoutjesdyk, B. Dunlap, J. Kohler & P. Swenson)
Richard Kelley Smith (J. W. Hammond, J. G. Jackson, R. W. Saubert & R. W. Mossman)
Robert P. Sperry (B. J. Eubank, G. J. Haulsewe, D. F. Smith & R. L. Cole)
R. F. Timo (T. P. Maroney, U. Colledan & L. Baulino)
Masao Tatsugami (T. Kaneko, K. Mori, & T. Kawashima)
W. J. Wells (W. H. Mayne, J. O. Parr, P. J. Rudolph & R. L. Milliken)

APPLICATION FOR TRANSFER TO ACTIVE MEMBERSHIP

Richard Harold Gervan (V. E. Child, J. F. Wright, J. W. Rogers & D. T. McCreary)
Judson B. Hughes, Jr. (B. W. Sorge, F. H. Agee, R. A. Paterson & M. Slavin)
Jack Grynberg (R. H. Benish, E. B. Wasson, G. Anderson & J. W. Carey)
Charles Leslie Lake (F. Searcy, L. E. Whitehead, H. M. Moody & A. W. Black)
Robert G. McBeath (J. L. Stephens, R. C. Dunlap, Jr.)
Thomas Gordon Michael (C. W. Blakey, E. H. Weltsch, B. F. Rummerfield & A. C. Austin)
Herman Rudolf Van der Meulen (G. F. Coote, A. E. Pallister, J. M. Hinson & M. Aydin)
William M. Oakley (W. H. Hawkes, Dr. B. A. Tuller, G. L. Ellis & R. L. Higgins)

ANNOUNCEMENTS

A new executive committee was announced at the annual meeting of the C.S.E.G. on February 18, 1960.

Shown, left to right, are the following: J. J. Hamilton—new C.S.E.G. Secretary, J. G. Goodwin—new C.S.E.G. Treasurer, P. J. Savage—new C.S.E.G. Vice-President, H. J. Kidder—retiring C.S.E.G. President. T. O. Hall—S.E.G. President, M. B. Dobrin—new C.S.E.G. President. F. Searcy—S.E.G. Vice-President.

THE SOUTHWEST LOUISIANA GEOPHYSICAL SOCIETY NAMES 1960 OFFICERS

The Southwest Louisiana Geophysical Society recently elected the following officers: Seated from left to right are Dick Hollenbaugh (Petty Geophysical Engineering Co.) Vice-President, Walter Hurt (Sohio) President; Standing left to right are R. Ned Pratt (Sun) Treasurer and Lucius Geer (Union Oil Company of California) Secretary.

S.E.G. President, T. O. Hall (*left*), gave the presidential address that got things off to a good start. A.A.P.G. President, Lewis G. Weeks (*right*) spoke on energy supply and demand during the next one hundred years.

S.E.G. President, T. O. Hall (*center*), presented awards for the Best Presentations of the 29th Annual International Meeting, to Francis Collins, Jr. (*left*) of the Atlantic Refining Company, and Frank J. McDonal of the Socony Mobil Oil Company.

PROCEEDINGS OF THE FIFTH WORLD PETROLEUM CONGRESS

Proceedings of the Fifth World Petroleum Congress are now available, according to Mr. E. V. Murphree, Chairman of the Board of Directors of the Fifth World Petroleum Congress.

The Proceedings consist of eleven volumes. There is a separate volume containing the technical papers and discussions for each of the ten Sections of the Congress. The General Volume describes the organization and events of the Congress and contains the General Lectures, speeches, and a list of all Congress members and their addresses.

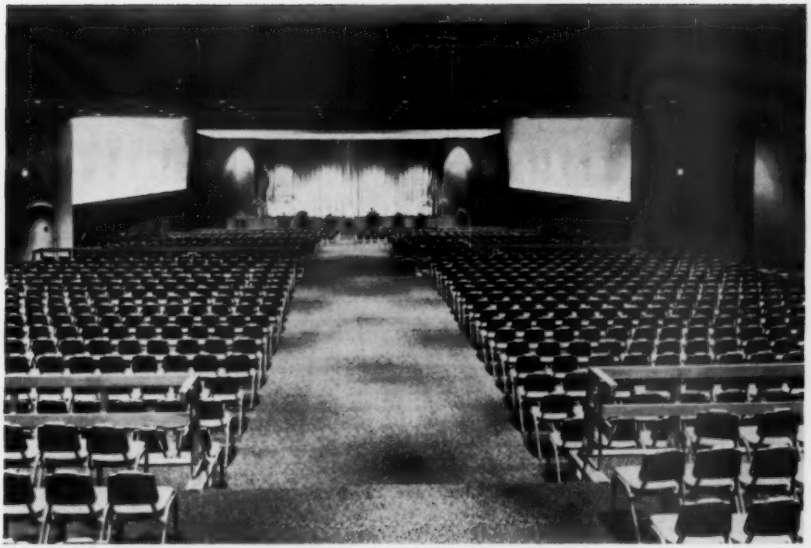
The technical volumes represent an unparalleled collection of up-to-date information supplied by outstanding leaders in the various fields of petroleum technology. As such, they are extremely valuable references for those working in these fields.

The Proceedings are now being mailed to Congress attendees and other groups who placed orders in advance. A limited number of copies are available for sale from the American Petroleum Institute's Publications Offices, 1271 Avenue of the Americas, New York 20, New York.

THIRTIETH ANNUAL INTERNATIONAL MEETING SOCIETY OF EXPLORATION GEOPHYSICISTS

The Thirtieth Annual Meeting of the SEG will be held next November 7–10 at the new Moody Convention Center in Galveston. This center offers ideal facilities for our meeting; it has two large meeting rooms on the second floor which can be thrown together as one if desired and a very large

Moody Convention Center (*center*), Galvez Hotel (*upper right*), Buccaneer Hotel (*lower left*).



The Moody Convention Center Assembly Hall where the technical session will be held.

exhibit space on the first floor. The facilities are generally similar to those of the Coliseum in Houston and the Memorial Auditorium in Dallas. The Moody Center is located facing the Seawall and the Gulf of Mexico and is between the Galvez and Buccaneer hotels and only a very short distance from either.

The general plans for the meeting are similar to those of previous years. Registration will begin on Sunday, November 6. Monday morning will be a free time for attendances at exhibits and renewing acquaintances. The meeting will begin officially with a kick-off luncheon at noon Monday with a talk by a prominent leader in exploration who will emphasize the over-all theme of the meeting. Monday afternoon will be devoted to presidential addresses, reports, and one or two outstanding papers. The Tuesday morning session is planned as a symposium on geology and geophysics and their mutual contributions to "Total Exploration." Tuesday afternoon will be devoted to a symposium at which will be presented recent developments in space technology with emphasis on mutual contributions of geophysicists to space technology and vice versa. Wednesday and Thursday will be devoted to general papers with two parallel Research Sessions on Wednesday and two parallel Mining Sessions on Thursday. The general plan is to have somewhat fewer papers than at previous meetings and to present material which will be of higher quality. To this end the assignment of papers to the program will be made on the basis of a complete manuscript or at least an extended abstract. This will require that material for papers be organized somewhat further in advance of the meeting than has been common in the past.

July 1, 1960 is the deadline for submittal of papers which has been tentatively set by the Program Committee.

At the present time there is, of course, plenty of room for good material. Members who are considering submitting papers to be given at this meeting are urged to do so immediately and to indicate their plans to the Program Chairman or to one of the local Program Committee Members as listed herewith.

L. L. Nettleton, Program Chairman, P. O. Box 22007, Houston 27, Texas
Lloyd Paitson, Vice-Chairman, P. O. Box 22007, Houston 27, Texas
James A. Boydstun, Union Producing Company, Box 1407, Shreveport, La.
P. J. Savage, Nance Exploration Co., Condon Bldg., Calgary, Alberta, Canada
B. A. Tuller, Pan American Petroleum Corp., Box 40, Casper, Wyoming
John W. Bolinger, Humble Oil & Refg. Co., Box 1271, Corpus Christi, Texas
Roger Heggblom, Bolivian Gulf Oil Co., Casilla 1458, Cochabamba, Bolivia
E. F. McMullin, Rayflex Exploration Co., 6923 Snider Plaza, Dallas 5, Texas
Arthur W. Black, Continental Oil Co., 1041 Continental Oil Bldg., Denver 2, Colorado
Ray F. Keller, General Geophysical Co., 10509-81 Ave., Edmonton, Alberta, Canada
R. H. Dana, Dana Explorations, Inc., 1301 W. T. Waggoner Bldg. Ft. Worth, Texas
Foster E. Endacott, Jr., El Paso Natural Gas Co., Box 977, Farmington, New Mexico
Sam P. Worden, Texas Instruments, Inc., 3609 Buffalo Speedway, Houston 6, Texas
John Babb, Delta Exploration Co., Inc., P. O. Drawer 2666, Jackson, Miss.
W. H. Dawson, The Carter Oil Co., P. O. Box 318, Billings, Montana
Royce E. Lawson, Humble Oil & Refg. Co., P. O. Box 1287, Roswell, New Mexico
C. Lane Howell, Sohio Petroleum Co., 1606 N. Broadway, Okla. City, Okla.
Nolan A. Webb, Richfield Oil Corp., 5900 Cherry Ave., Long Beach, Calif.
E. E. Fickinger, Continental Oil Co., Box 431, Midland, Texas
Fred G. Knight, The Ohio Oil Co., Box 193, Bakersfield, California
B. F. Fulton, Imperial Oil Ltd., Derrick Bldg. Regina, Sask., Canada
J. T. McMaster, Pan American Petroleum Corp., 414 Carondelet Bldg. New Orleans 12, Louisiana
P. J. Rudolph, Petty Geophysical Engineering Co., P. O. Drawer 2061, San Antonio, Texas
John A. Standridge, Phillips Petroleum Co., Box 1463 Oil Center Station, Lafayette, Louisiana
J. E. Hawkins, Seismograph Service Corp., P. O. Box 1590, Tulsa 1, Oklahoma
K. L. Cook, University of Utah, Dept. of Geophysics, Salt Lake City, Utah
D. F. Warner, Cities Service Petroleum Corp., Apartado 3936, Caracas, Venezuela

RESEARCH SESSION

The Research Session, tentatively scheduled for Wednesday morning and afternoon, will include papers on highly technical subjects and basic research. Such papers should be submitted to R. R. Thompson, Chairman of the Research Session, Humble Oil & Refining Co., Box 2180, Houston 1, Texas, or to one of the following committee members:

Mr. J. F. Bayhi, Jersey Production Research Co., 1133 North Lewis Ave., Tulsa 10, Oklahoma
Dr. F. G. Blake, Jr., California Research Corp., P. O. Box 446, La Habra, California.
Dr. Theodore R. Madden, Massachusetts Institute of Technology, Dept. of Geology and Geophysics, Cambridge 39, Massachusetts
Mr. Robert B. Rice, The Ohio Oil Co., P. O. Box 269, Littleton, Colorado.
Dr. F. A. Van Melle, Shell Oil Co., 3737 Bellaire Blvd., Houston, Texas
Mr. Kenneth H. Waters, Continental Oil Co., P. O. Drawer 1267, Ponca City, Oklahoma.
Dr. J. L. Worzel, Lamont Geological Observatory, Torrey Cliff, Palisades, New York

MINING GEOPHYSICS SESSION

The Mining Session, tentatively scheduled for Thursday morning and afternoon, will include papers on mining geophysics. Such papers should be submitted to Mr. John Sumner, Chairman of the Mining Session, Phelps-Dodge Corp., Box 991, Douglas, Arizona, or to one of the following committee members:

Harold M. Mooney, University of Minnesota, School of Mines, Minneapolis, Minnesota
Walter E. Heinrichs, Jr., 2943 E. Chula Vista Dr., Tucson, Arizona.
Phillip C. Hallof, McPhar Geophysics, Ltd., 139 Bond Ave., Don Mills, Ontario, Canada
Robert Bowman, Bear Creek Mining Co., 516 Acoma St., Denver, Colorado

Don R. Mabey, Geophysicist U. S. Geological Survey, Geophysics Branch, Menlo Park, California
Mr. Robert G. Van Nostrand, Gulf Oil of Libya, Box 599, Tripoli, Libya

THEME

The theme of the meeting is "Total Exploration." To follow out this theme the meeting will emphasize the mutual contribution of various geophysical methods and other data to the over-all exploration problem. The symposium on geology and geophysics is planned as a special contribution to this theme. In a broader sense the planned symposium on the relation of geophysics to space exploration is also consistent with this theme.

W. B. Lee, general chairman of the convention.

30TH ANNUAL INTERNATIONAL MEETING PLANNERS

L to R: Richard H. Parker, entertainment; Dean Walling, SEG Vice-President; W. T. Lea, housing; W. H. Gibson, exhibits; A. A. Becker (behind Mr. Gibson) registration; R. M. Rogers, housing; Mrs. Paul Farren, ladies' program; T. L. Kunkel (behind Mrs. Farren), exhibits; E. T. Miller, finance; Grace Bingham, publication; R. C. Hilton, arrangements; Sidney Schafer, publications; Robert B. Baum, registration; G. P. Montgomery, finance and general vice-chairman; W. Harlan Taylor, publicity; L. B. McManis, entertainment; L. L. Nettleton, Technical program; T. O. Hall (behind Dr. Nettleton), SEG President; O. B. Manes, arrangements; and Lloyd Paitson, technical program. W. B. Lee, general chairman, and C. P. Harkins, transportation, were not present when the picture was taken.

CORRECTION

The abstract, by C. H. Savit on p. 1132 of the December 1959 issue of GEOPHYSICS, was published erroneously in that it was a modified version of C. A. Woods abstract on p. 1150.

PERSONAL ITEMS

OBITUARY

ROBERT WILKES BALDWIN, assistant manager of Newmont Exploration's Geophysical Department, died Sunday afternoon, July 26th, some hours following a helicopter crash in an abortive landing attempt on Gilman Glacier, several miles north of Mount Crillon, Alaska.

Mr. Baldwin was born in Toronto, Canada and graduated from Upper Canada College boys' school, after which he served with the Royal Canadian Air Force as a radar officer in the Near East and the United Kingdom. He was awarded the B.Sc. degree from the University of Toronto, Engineering Physics course 1949, having achieved honors standing in all four years.

Directly on graduation he joined Newmont's geophysical exploration and development group then being formed. His efforts contributed markedly to the early developments and use of the induced polarization method and to the evolution of the rigidly attached helicopter electromagnetic system, the field and interpretive procedures for which owe much to Bob Baldwin's work.

His induced polarization survey at Cuajone, Peru with rudimentary equipment, early 1952–1954, outlined sulphides, in part under 500–600 ft of later volcanics, and stimulated the additional drilling that proved the Cuajone ore body of the present Southern Peru Copper Company group. See *Mining Engineering*, volume 11, number 3, March 1959, pp. 307–314.

With enthusiasm and humor he had carried his work to many lands, the peaks and caves of Peru, the arroyos and valleys of the Southwest and Mexico, the lake chains and tundra of the Canadian Barrens and the rain-drenched humid islands of the Philippines. Personal travel had reached Egypt, Asia Minor, Scandinavia and Japan.

In June of 1954 at Arequipa, the white city of Peru, Bob Baldwin married Blanca Rivertti and in 1955 returned with her to the United States. His wife and three children: Lawrence, Carmen and Robert, survive.

Bob Baldwin's great strength was his zest, humor and equitability to the trials, reverses and uncertainties of exploration life. In a small frame and beneath a quiet manner he packed the indominability of the early pioneer. To him, as but to few, applied Kipling's pointed lines:

"If you can meet with triumph and disaster,
And treat those two impostors just the same;
. . . . . .
And which is more . . . you'll be a man, my son."

Bob Baldwin has left his example and influence with us here as few have done. We know his buoyant spirit moves onward.

ARTHUR A. BRANT

OTHER PERSONAL ITEMS

ED HAYE, President of Photogravity Co. Inc. announced today that Geologist-Geophysicist TOM LINDHOLM has joined the company as Executive Vice-President. Mr. Lindholm, formerly of Denver, Colorado, worked for California Company in charge of the Gravity and Magnetics Dept.

JACK N. MOREHEAD, recently of Midland, Texas has opened an office as a consultant in exploration problems in southeastern Kansas. His Office is located in Chanute, Kansas.

W. DOW HAMM was elected Vice-President of The Atlantic Refining Company, effective March 15, Mr. Henderson Supplee, Jr., President announced.

Hamm was appointed general manager of crude-oil production effective the same date. In this capacity he succeeds Laurence A. Sunkel, who will devote his attention to special crude-oil production activities, pending his retirement early next year. Sunkel will continue as a director and a Vice-President of Atlantic.

A graduate of the University of Oklahoma, Hamm joined Atlantic in 1942 as chief geologist. He has served as manager of domestic and foreign exploration since 1952.

The Atlantic Refining Company has announced the award of unrestricted grants of $1,000 each to ten colleges and universities in the south, southwest, and midwest.

Receiving the $1,000 grants are University of Houston, Texas Technological College, Rice Institute, Saint Louis University, Southern Methodist University, Texas A & M College, University of Texas, Tulsa University, Washington University, and Tulane University.

An agreement has been signed for the exchange of 100% of the outstanding stock of Western Geophysical Company of America for common stock of Litton Industries, it was reported jointly by board chairmen Charles B. Thornton of Litton and Henry Salvatori of Western Geophysical. The amount of Litton stock involved was not disclosed.

Western Geophysical, as an operating subsidiary of Litton, will continue with all of its present officers, directors, and present organizational structure unchanged, with Dean Walling as president and Henry Salvatori as chairman of the board and chief executive officer, the announcement stated.

R. G. McCuistion, Supervisor for Empire Geophysical, Inc., has been transferred from their Midland Regional Office to Farmington, New Mexico. Mr. McCuistion will be assigned to supervision of field operations and interpretation for the firm's seismic operations in the Four Corners Area.

Southwestern Industrial Electronics Company, a division of Dresser Industries, Inc., 10201 Westheimer Road, has been awarded a contract by the Martin Company, Orlando, Florida, to build 240 signal conditioning modules for use on the Pershing Missile. The modules feature S.I.E.'s latest advancements in solid-state circuitry and plug-in packaging design.

George A. Peck was appointed to the presidency of Southwestern Industrial Electronics Company, of Houston, Texas, one of the Dresser Industries.

Mr. Peck comes to S.I.E. from the Stromberg-Carlson Company of Rochester, New York. With Stromberg-Carlson, Mr. Peck was Vice-President and General Manager of the Electronics Division.

Mr. Peck is a native of Buffalo, New York and received his elementary and higher education in Potsdam, New York, where he graduated as a chemical engineer from Clarkson College of Technology in 1937. Prior to joining Stromberg-Carlson in 1942, he was associated with the General Cable Corporation, the Upson Company, and the Standard Cable Corporation.

Mr. Peck is a member of the Society of Plastics Engineers, The Armed Forces Communications Association, The American Society of Naval Engineers, The American Ordnance Association, The American Management Association and the American Society of Chemical Engineers. He is married and the father of three children. In his new position as President of S.I.E., he will reside in Houston, Texas.

Keith R. Beeman, President of Southwestern Industrial Electronics Co., Houston, announced today that he is vacating his present position effective February 20, 1960. Mr. Beeman was co-founder of the company and its president since S.I.E. was founded in 1945.

Mr. Beeman is accepting a new position with the parent company, Dresser Industries, Inc. In his new position, Mr. Beeman will continue to make his headquarters in Houston.

Richard L. Fentem, Amerada Petroleum Corporation, has been promoted to Assistant Geophysical Supervisor. He is now on loan to Oasis Oil Co. of Libya Stationed in Tripoli.

Don A. Hansen left the employ at Bear Creek Mining Company and established a management consulting firm to serve the mineral exploration industry.

His associates in the present enterprise are Dr. George H. Hansen, formerly chairman of the Department of Geology at the Brigham Young University. Dr. Hansen is at present working in Indonesia, but upon his return will work with the organization.

A second associate is Dr. Albert W. Heyer, Jr., a member of Schwartzlander and Heyer, consulting psychologists, Denver, Colorado. Dr. Heyer will provide professional assistance in the selection and development of personnel of the client organizations.

REX H. WHITE, formerly chief geophysicist, Producing Division, Karachi, Pakistan, for Standard-Vacuum Oil Company is now chief geophysicist for Mobil Oil Francaise with headquarters at 54 Rue de Londres, Paris 8e, France.

R. E. DOE has been appointed to the position of Geophysics Associate—Applied Geophysics, La Habra Laboratory. He will be responsible for new methods development and application in the Geophysics Development Division.

Mr. Doe has been with the Standard Oil Company of California since 1948. During the last two years he held the position of Staff Geophysicist with the Chevron Oil Company in Houston.

B. C. JONES has resigned his position as geophysicist for the Superior Oil Company to take a position as geophysicist with the Ohio Oil Company, Box 3128, Houston, Texas.

JOHN MCCORMACK has been appointed an Assistant Vice-President. He will continue in his duties as controller of GSI, but, in addition will co-ordinate the activities of the Personnel, Equipment and Industrial Engineering Departments. McCormack has been with GSI since 1957.

J. W. THOMAS, GSI Vice-President and formerly manager of marketing has announced his intention of retiring later in the year, after 30 years with GSI. He will continue to be associated with the petroleum exploration firm.

R. H. RAINEY has been named to succeed Thomas as manager of marketing. Rainey, who joined GSI in 1947, has served as a field supervisor in the United States, Canada, and Australia. His last field post was as Far East operations manager in Singapore.

ROBERT RYAN, formerly a junior seismologist with Mobil Oil Co., is now a geologist for the Central Illinois Light Company.

C. HAYDEN ATCHISON has been promoted from division exploration manager to exploration co-ordinator for the British American Oil Producing Co.

REX WALLING, formerly district manager and division manager at Odessa for Grant Oil Tool Company, was transferred to Los Angeles and promoted to field supervisor in charge of branch operations.

CALENDAR OF MEETINGS

1960

June

9–11 Acoustical Society of America, Spring Meeting, Providence, R. I.
15–17 American Physical Society, Meeting, Montreal, Quebec.
19–24 American Institute of Electrical Engineers, Summer General Meeting, Atlantic City, N. J.
27–29 Institute of Radio Engineers, National Conference on Military Electronics, Washington, D. C.

August

8–12 American Institute of Electrical Engineers, Pacific General Meeting, San Diego, California.
23–25 Association for Computing Machinery, National Meeting, Milwaukee, Wisc.

October

2–5 Society of Petroleum Engineers of AIME, Fall Meeting, Denver, Colorado.
12–14 Third Annual Meeting, Southwestern Federation of Geological Societies, Abilene, Texas.
19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.
31–Nov. 2 GSA Annual Meeting, Denver, Colorado.

November

3–4 Pacific Section AAPG, Los Angeles
7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston, Texas.
14–16 API, Chicago, Illinois.

1961

February

19–23 AIME Annual Meeting, St. Louis, Missouri.

March

20–23 IRE National Convention, New York City.

April

24–27 AAPG-SEPM Annual Meeting, Denver, Colorado.

October

8–11 Society of Petroleum Engineers of A.I.M.E., Annual Meeting, Dallas, Texas
18–21 AAPG Mid-Continent Regional Meeting, Amarillo, Texas.
25–27 Gulf Coast Association of Geological Societies, San Antonio, Texas.

November

2–4 GSA Annual Meeting, Cincinnati, Ohio.
5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver, Colorado.
13–15 API, Chicago, Illinois.

1962

March

26–29 AAPG-SEPM Annual Meeting, San Francisco, California.
26–29 IRE National Convention, New York City.

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta.
7–10 Society of Petroleum Engineers of A.I.M.E. Annual Meeting, Los Angeles, California.

Oct. 31–Nov. 3 Gulf Coast Ass'n of Geological Societies, New Orleans, La.
12–14 GSA Annual Meeting, Houston, Texas.

1963
March
25–28 AAPG-SEPM Annual Meeting, Houston, Texas.
October
6–9 (Same as above only in New Orleans)
24–28 Society of Exploration Geophysicists, 33rd Annual International Meeting, New Orleans, La.

November
13–16 Gulf Coast Ass'n of Geological Societies, Hot Springs, Ark.

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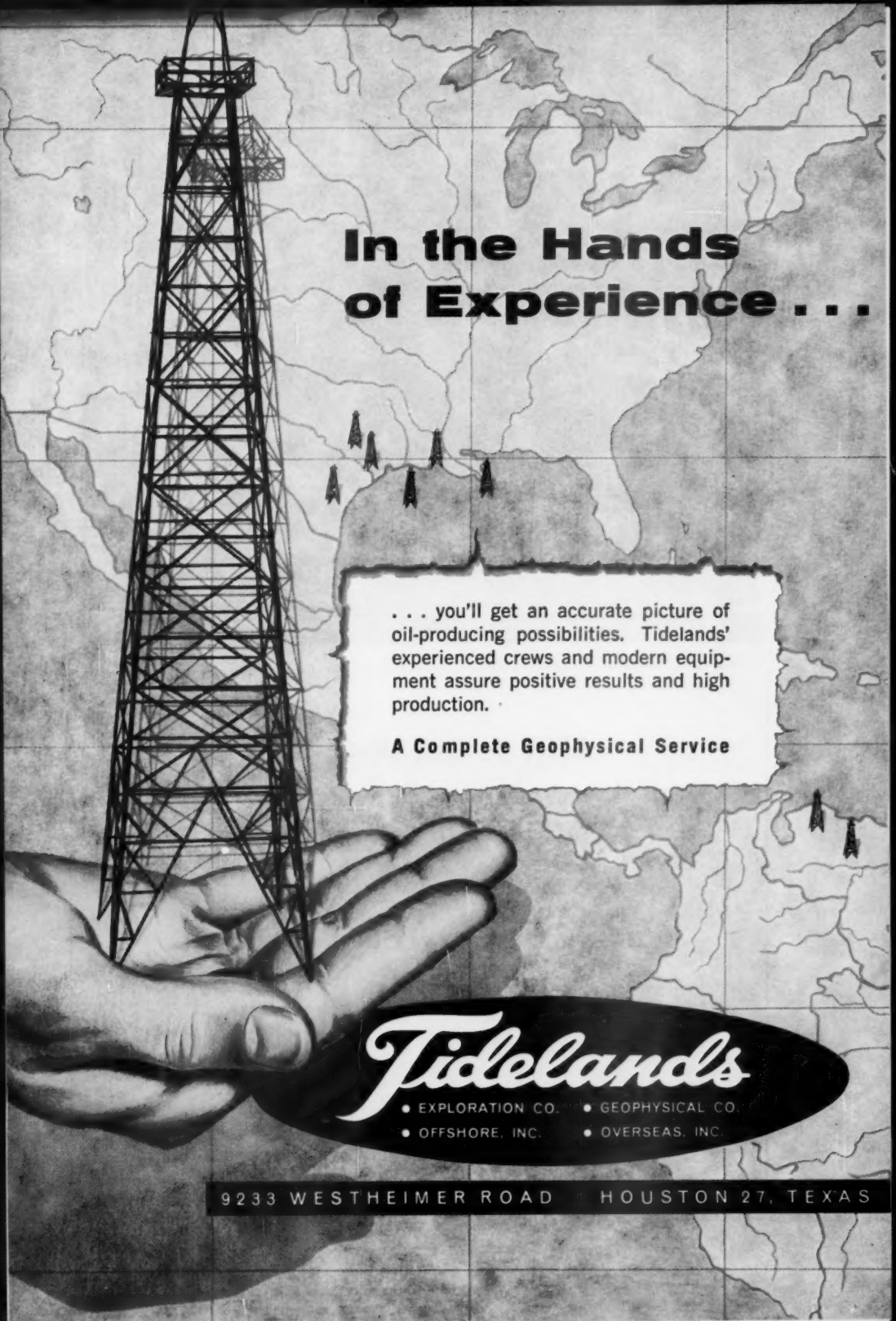
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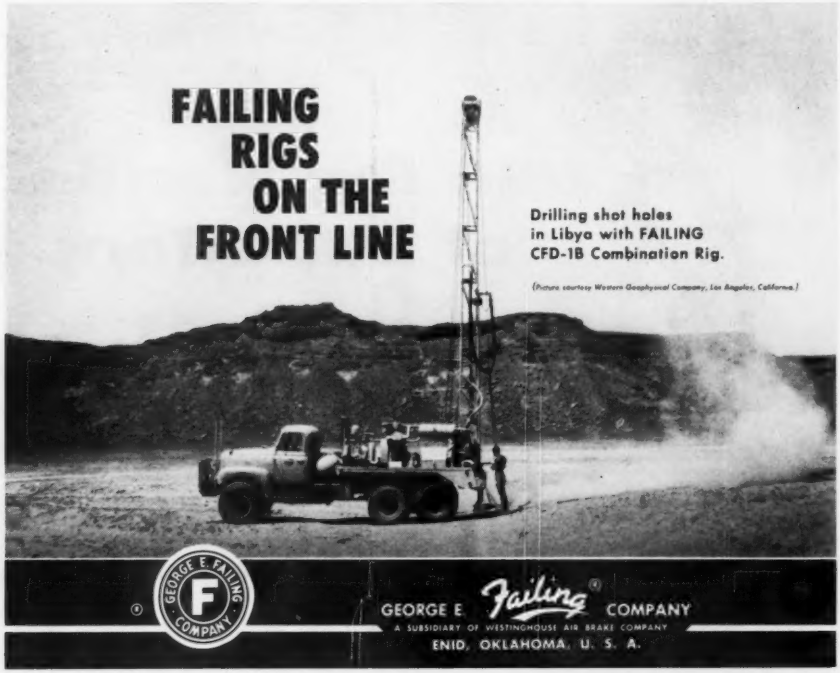

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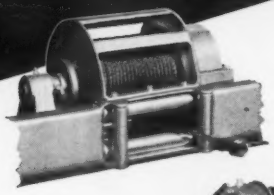

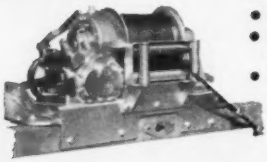

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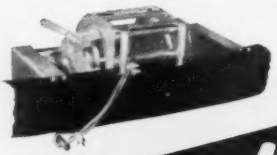

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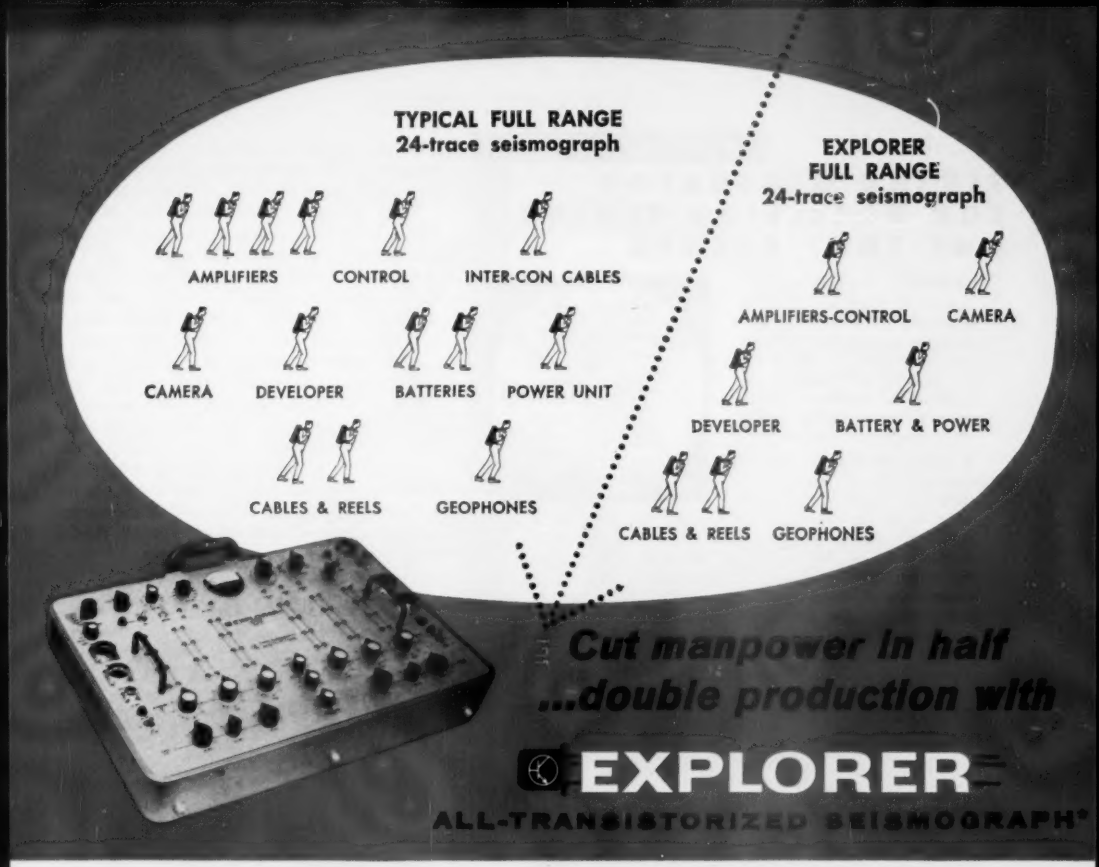

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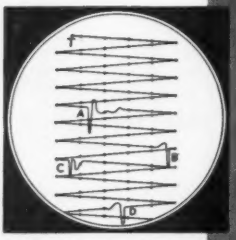

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(Continued from page 10)

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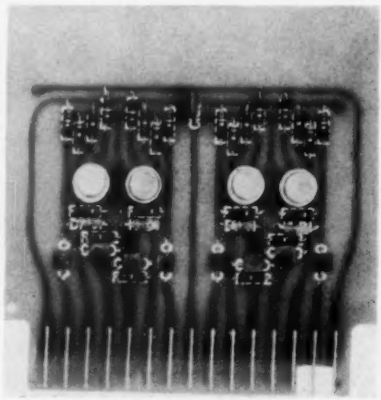

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(Continued on page 46)

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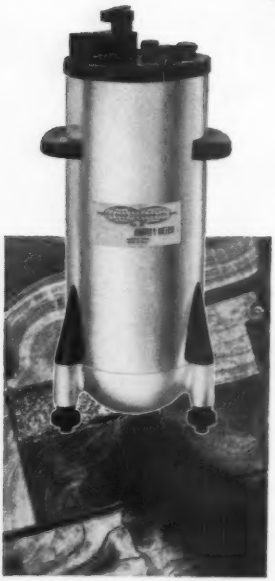

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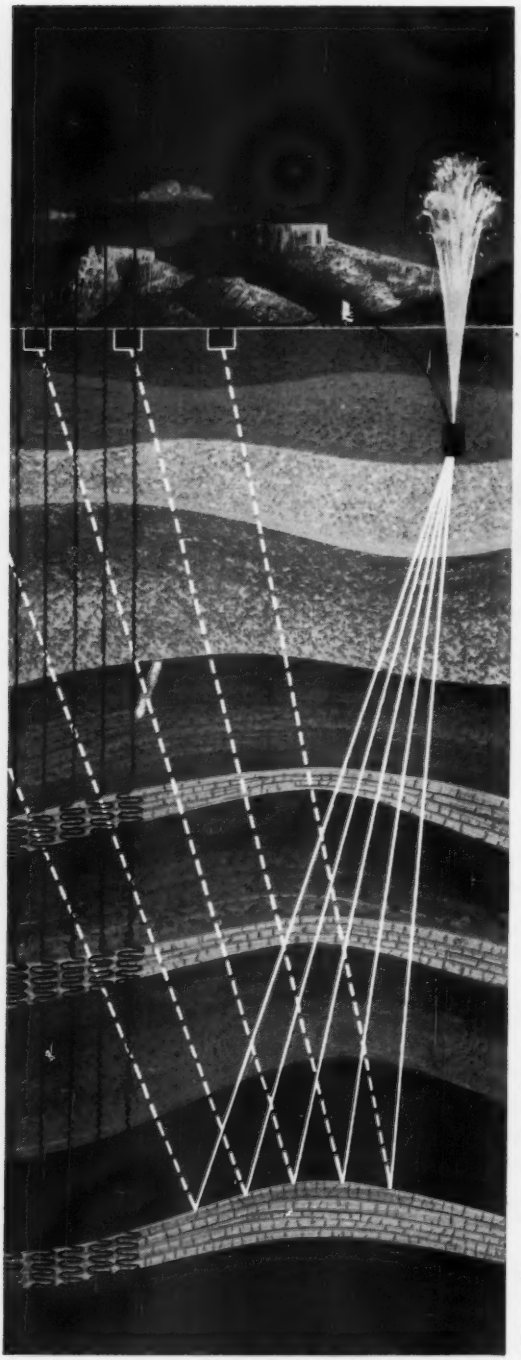

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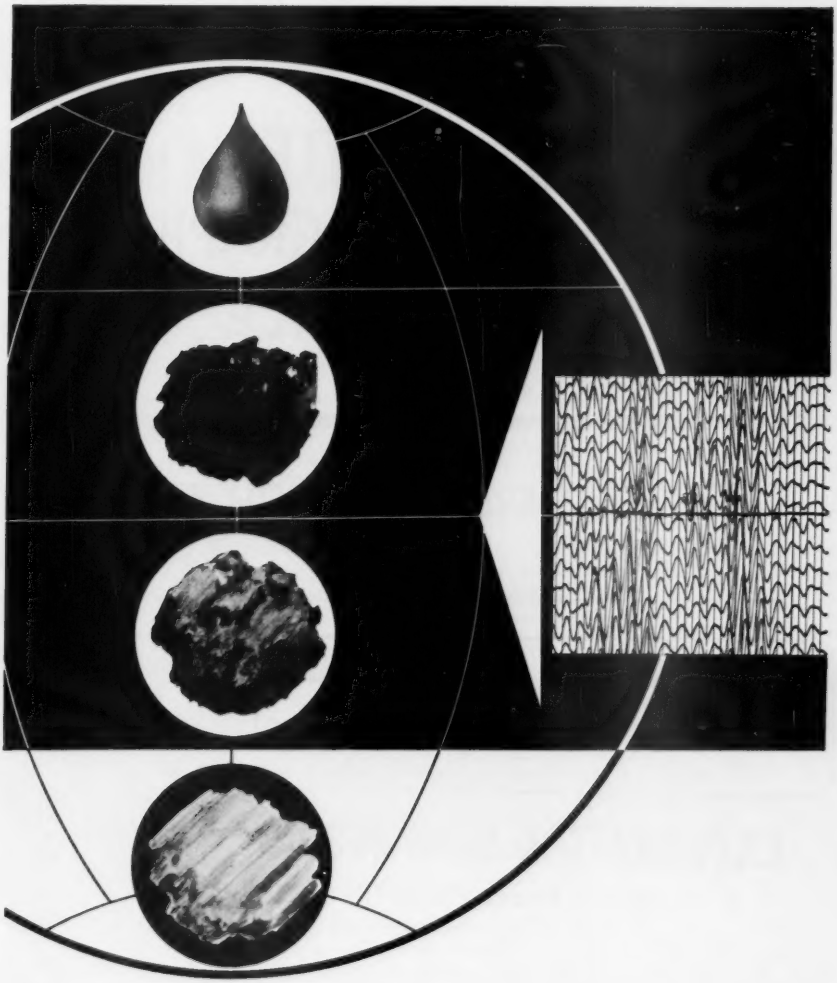

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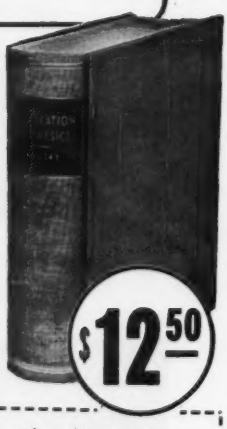

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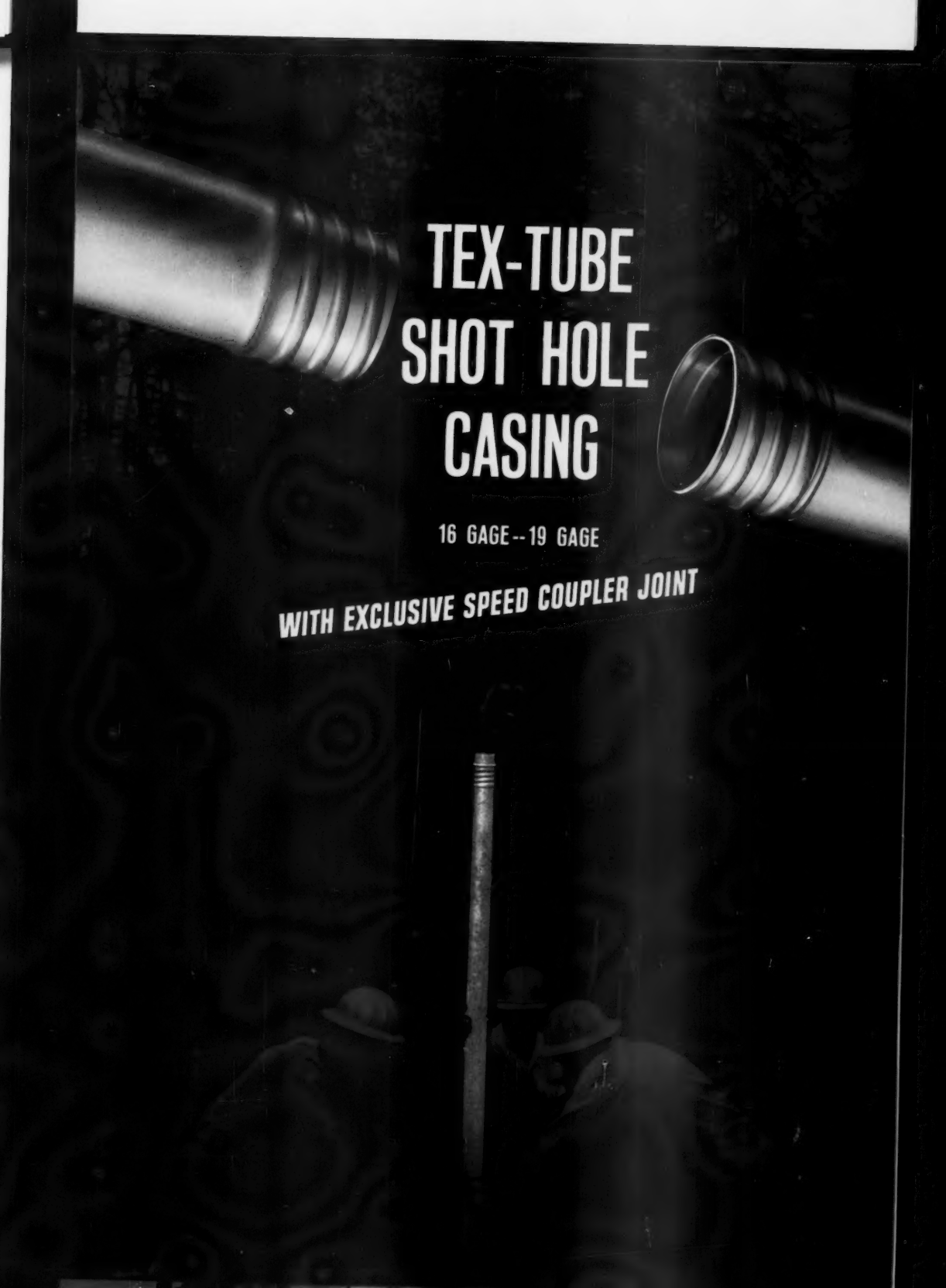
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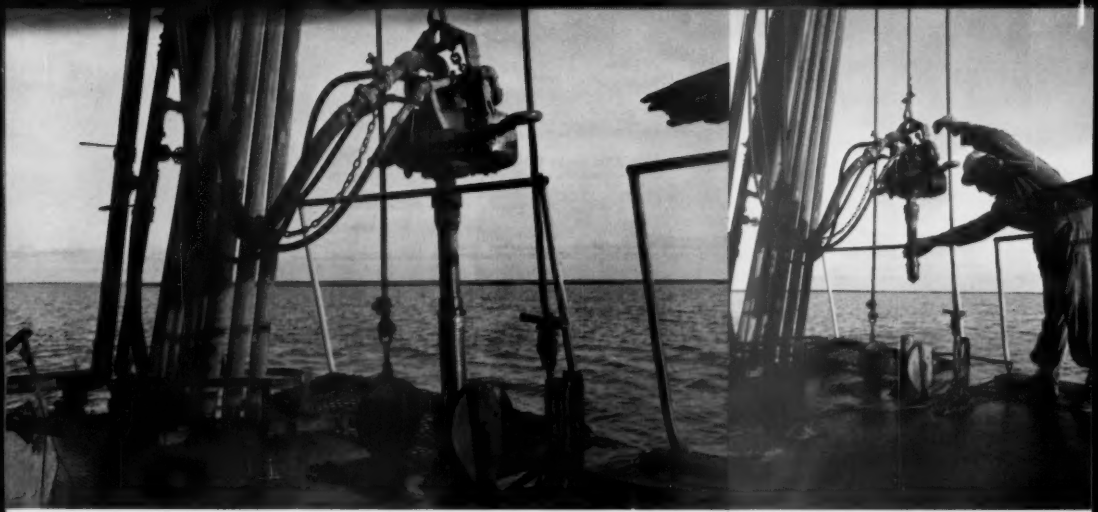

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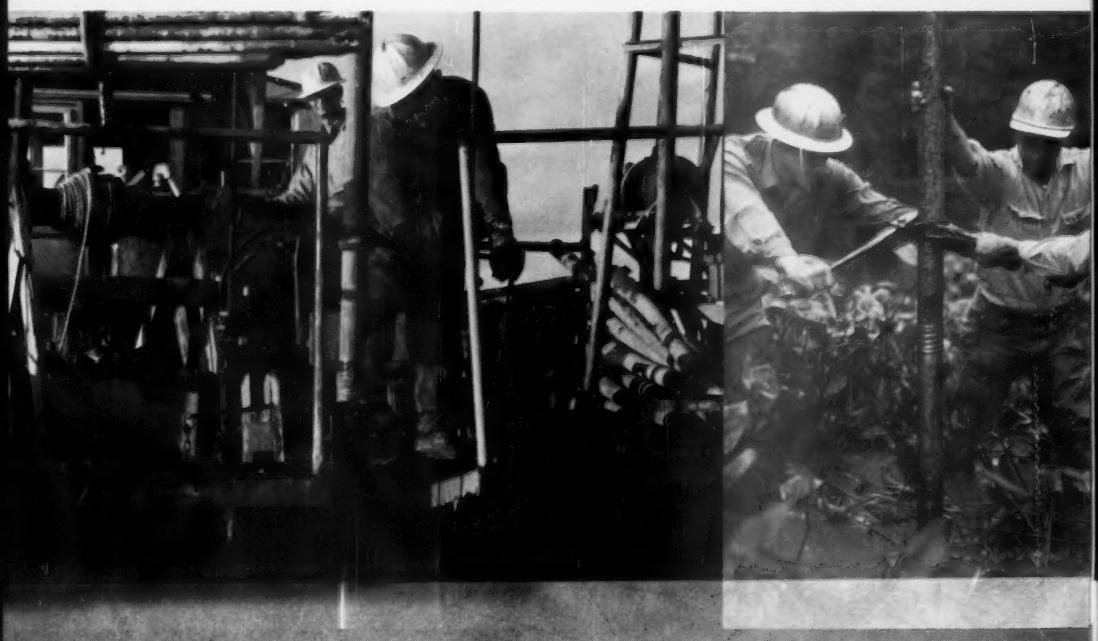

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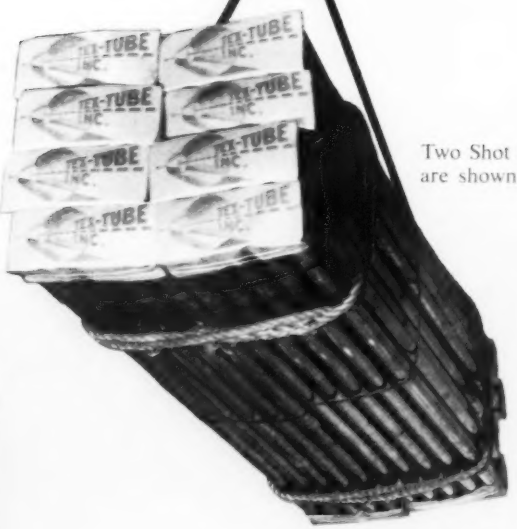

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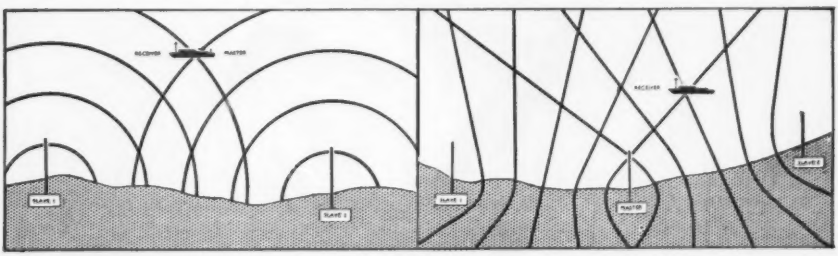

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(Continued from page 28)

POWER SPECTRUM COMPUTER

A dynamic range of approximately 8 decades of power for frequencies from 1 cps to 10 kc is one feature of a new power spectrum computer built by Applied Research Associates. Input signals, either direct or from magnetic tape, are modulated into the pass band of maximally flat, tripple stagger-tuned filters having fixed bandwidths from 1 cps to 100 cps. The filter output is accurately squared and integrated to give the power density spectrum. **Applied Research Associates, 6541 N. Lamar, Austin, Texas.**

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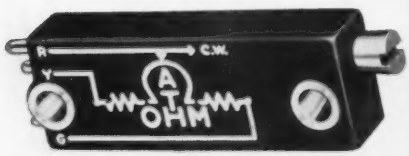

A new sub-miniature trimmer potentiometer for vitually all general purpose applications has been announced by Atohm Electronics. Identical in size to their MIL Quality W-5 series, the W-51 trimmer has a standard range of resistances from 10 ohms through 100,000 ohms, with tolerance ± 10%. These units, having .750 inch mounting hole centers, are available with 12 inch flexible insulated wire leads, (W-51-F), solder lugs, (W-51-L), end mounted printed circuit pins, (W-51-P1).

For complete engineering data, contact **Atohm Electronics, 7648 San Fernando Road, Sun Valley, California.**

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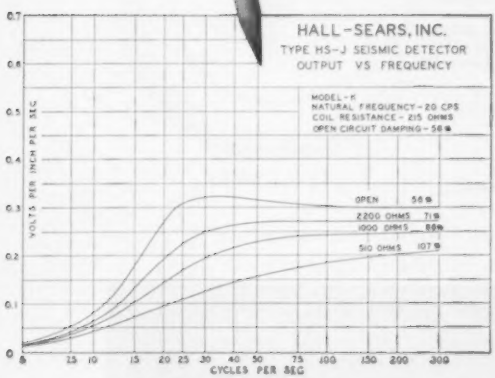

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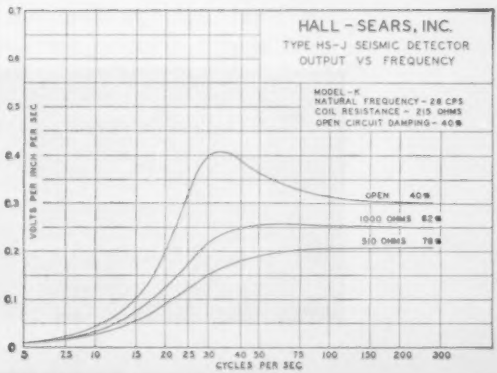

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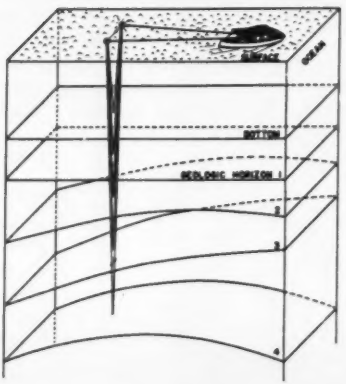

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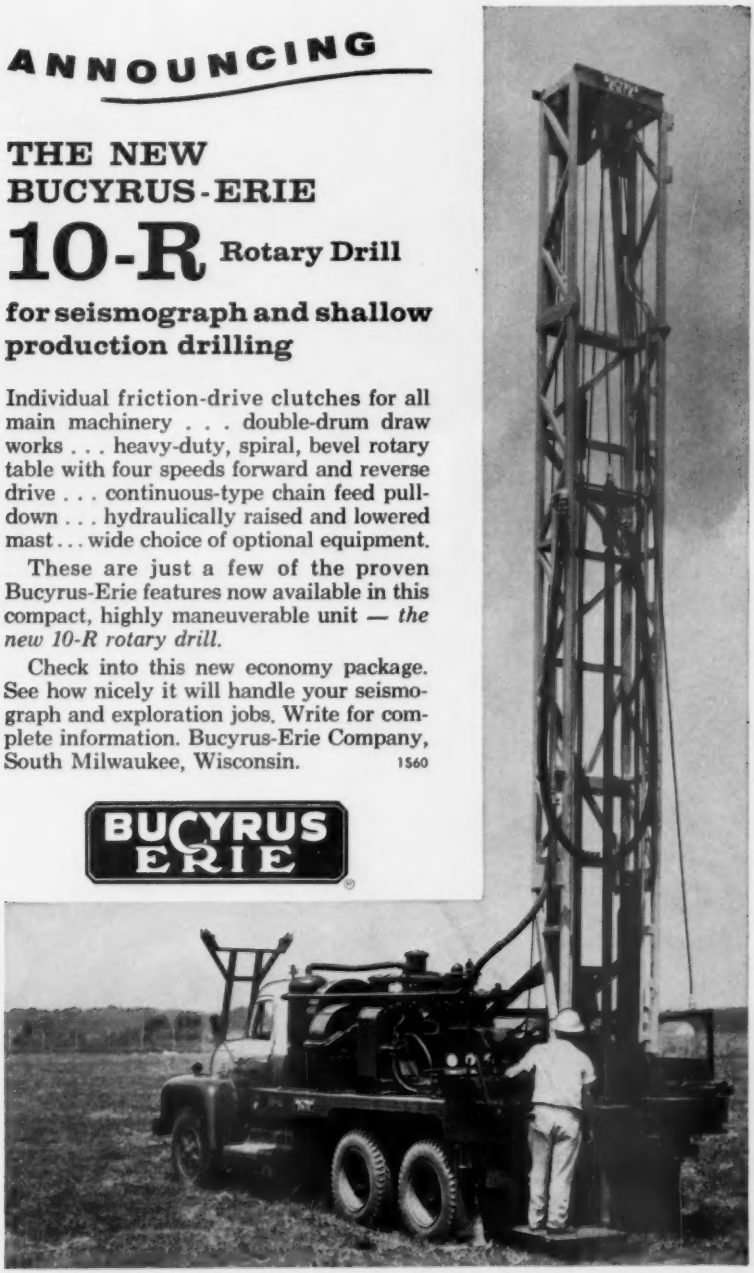

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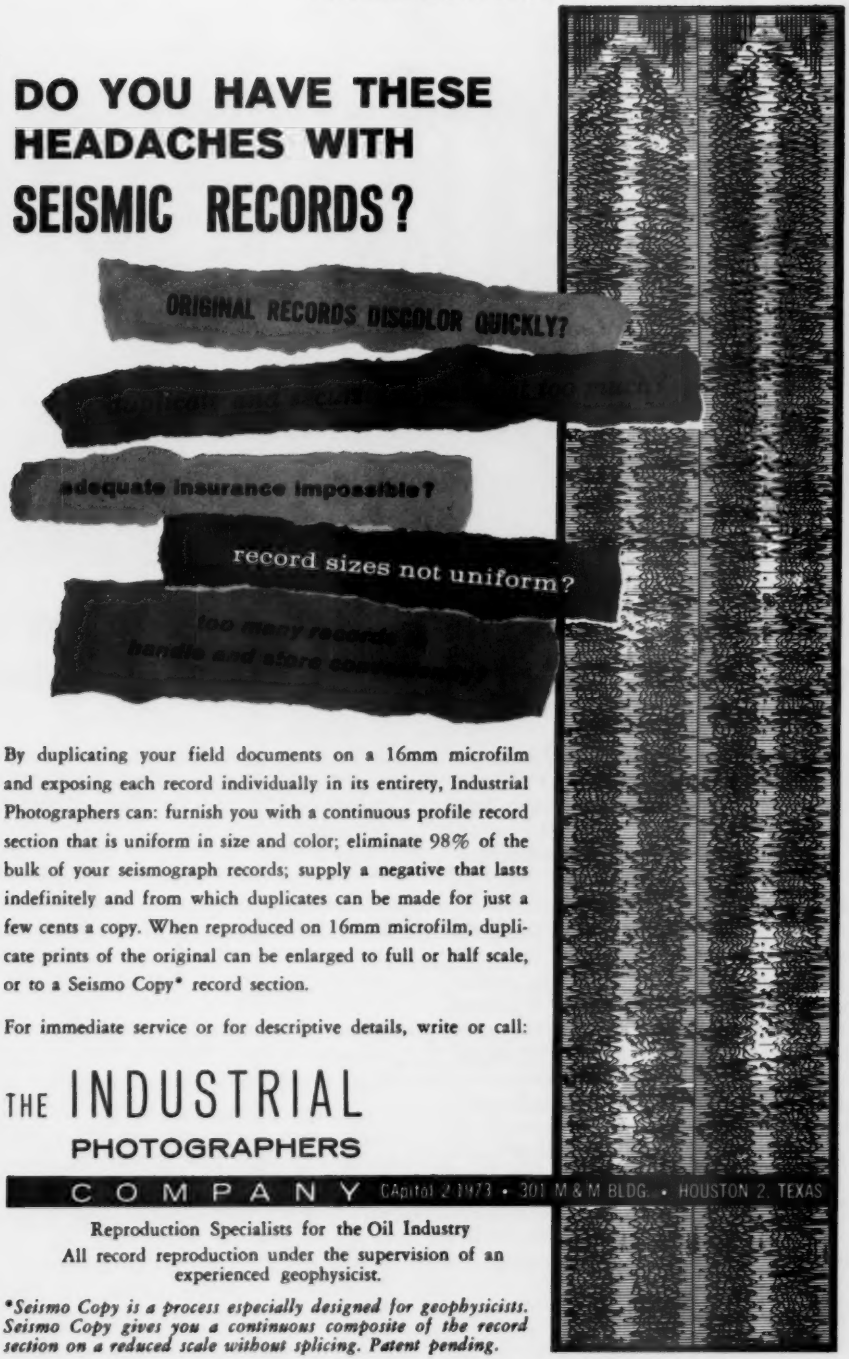

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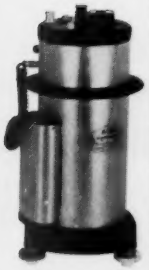

When requesting a quotation, copy the specification categories in this column and specify the values desired from those found under the respective meters.	the *Master*	the *Prospector*	the *Pioneer*	the *Educator*
Minimum Recommended Operating Range—Specify to nearest 100 mgls.* plus latitude and elevation indication	3000 mgls.	3000 mgls.	2400 mgls.	Limited . . . Will be at least 1600 mgls.
Minimum Total Operating Range (Reset) —Specify to nearest 100 mgls.*	5200 mgls.	5200 mgls.	4000 mgls.	Limited . . . Will be at least 2000 mgls.
Small Dial Range	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant	800 Dial Divisions x Small Dial Constant
Small Dial Constant—Specify constant desired*	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	0.10-1.00 mgl./ Dial Division
Small Dial Calibration Linearity over full range	1 part in 1000	1 part in 1000	1 part in 1000	1 part in 1000
Small Dial Reading Accuracy	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division
External Temperature Control	Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted.	None	None	None
Small Dial Mechanism	Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.		Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.	
Large Dial Range — Specify range desired*	800 Dial Divisions x Large Dial Constant			Geodetics not available
Large Dial Constant	Standard 6.5 to 12.0 mgls./D.D.			Geodetics not available
Large Dial Calibration over full range (8 turns)	Curve furnished with values accurate to one part in 1000—measured over full range (8 turns).			Geodetics not available
Size, Inches: Diameter Height	7" 14"	7" 14"	5½" 10½"	5½" 10½"
Weight, Pounds: Net Including carrying case	9¾ lbs. 18 lbs.	7½ lbs. 15¾ lbs.	5⅛ lbs. 12 lbs.	5⅛ lbs. 12 lbs.
*Price of meter is determined mostly by the Ranges and Dial Constant Specified.				

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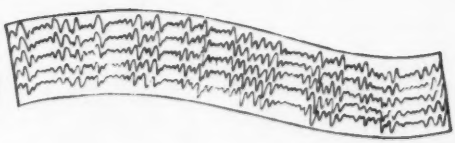

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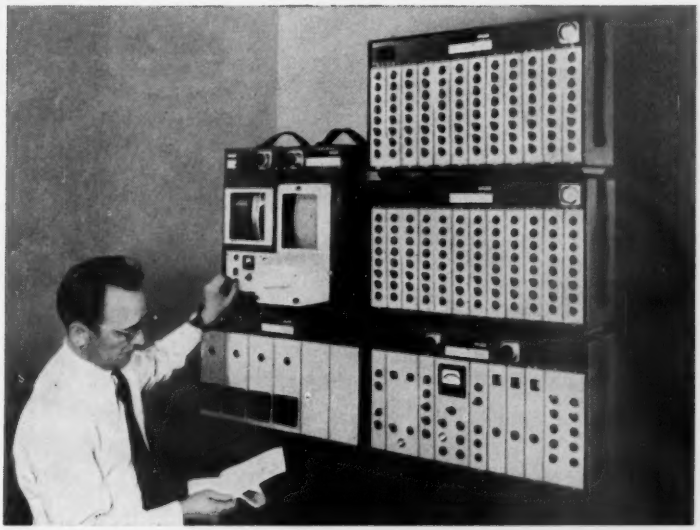

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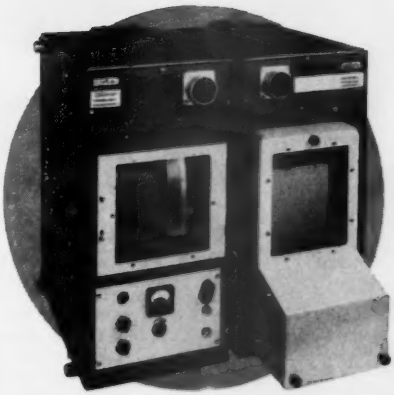

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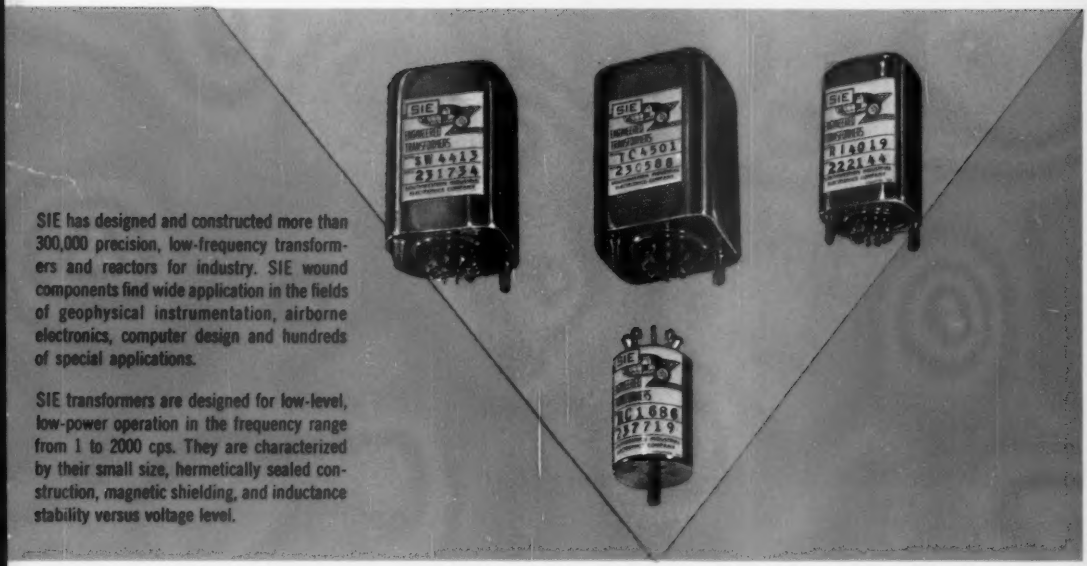

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Input	RI-1201	500CT/125	157,000CT	8	11	92	—	10	8 5	1:17 7
	SI-2028	500CT/125	340,000CT	40	53	272	—	1 5	1 5	1:26
Output	RO-1203	20,000CT/5000	50CT, 25, 12.5, 3	—	1280	4000	20	2	10	20:1
	TO-2330	40,000CT/10000	50CT/12.5	—	2300	3850	12 5	1 6	6 7	28:1
Interstage	RA-1202	10,000CT/2500	90,000	270	330	2230	8850	7	3 5	1:3
	SA-2321	10,000CT/2500	90,000	585	690	2100	21000	3 8	3 5	1:3
AVC Output	SO-1549	20,000CT	60CT/15 500CT	—	825	3300	17 100	—	—	18.5:1 6.3:1

	MODEL NO.	INDUCTANCE AT 30 CPS HENRIES		Q = WL/R AT 100 MV			DC RES. OHMS	PERCENTAGE TAPS
		AT 100 MV	AT 1 V	30 cps	Max.	At cps		
Reactor	RC-1205	1050	1120	12	12 5	60	11,000	2-2% + 2-4%
	SC-1572	3600CT	3800	13	13 5	42	20,000	None
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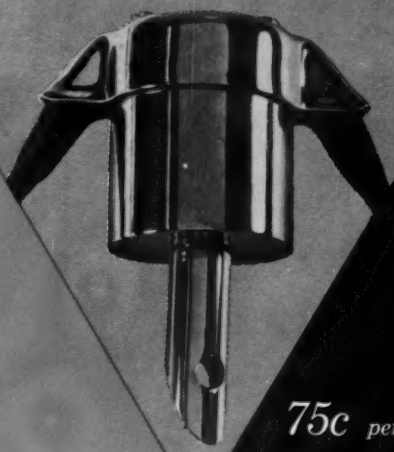

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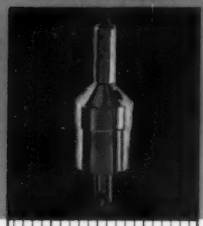

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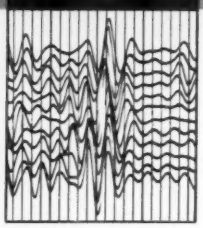

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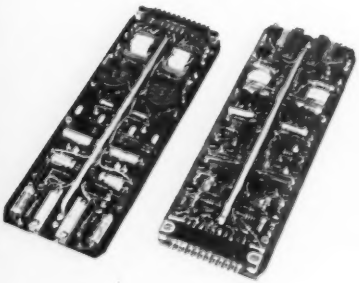

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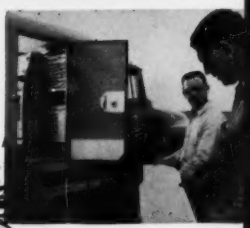

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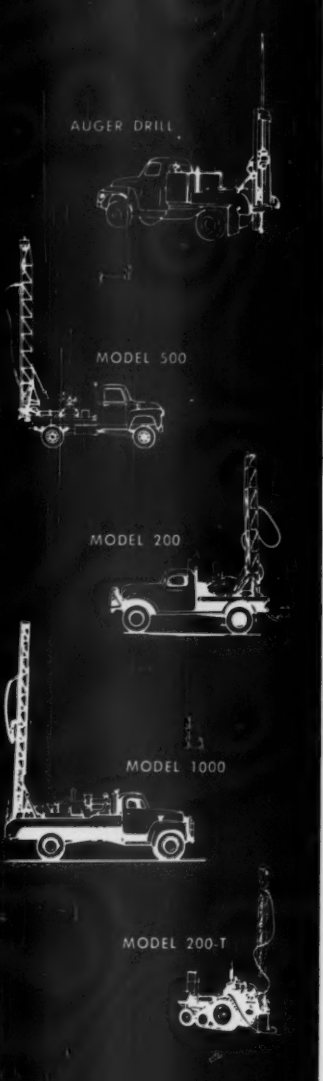

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Kodak

As far as he is concerned, The Thumper must be the name of a character in a bedtime story for the kids.

He has never made a study of how to ripen a photographic emulsion.

Paul R. Crookshank (left) of Kodak meets D. P. Melton, Director of the Geophysical Laboratory at Robert H. Ray Geophysical Companies, Houston. Mr. Melton's seismographic crews around the world, including those who employ The Thumper to generate seismic energy by dropping a 6000-lb. weight nine feet, have to process *Kodak Linagraph 480 Paper* under extremely adverse conditions to obtain unfiltered records from magnetic tapes for immediate visual checking. Mr. Crookshank, who devised *Kodak Linagraph 480 Paper,* is reporting to Mr. Melton the recent addition to this paper of a brightening agent which makes the background much whiter and the lines of the record correspondingly more emphatic. Mr. Crookshank's major accomplishment in *Linagraph 480,* however, is still its tolerance to mishandling in processing.

Difficult as it may be to believe, in the subsequent conversation it developed that Paul's dad had been school superintendent around Carrollton, Mo., the very same town where Don Melton was born and brought up. Now they have more in common than just an interest in **Kodak Linagraph 480 Paper.**

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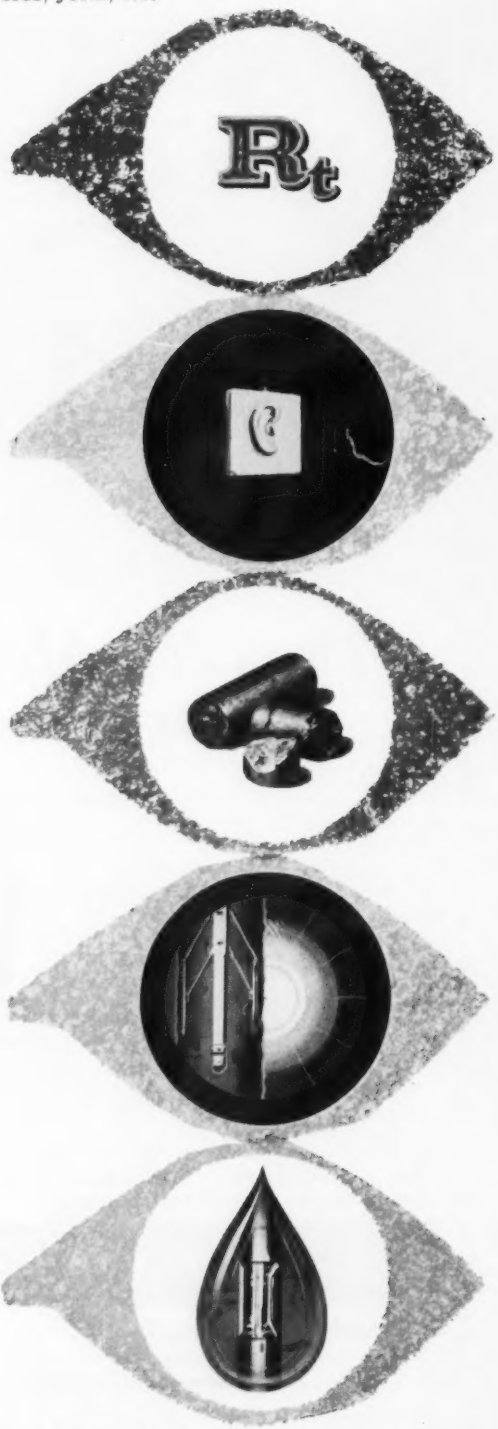

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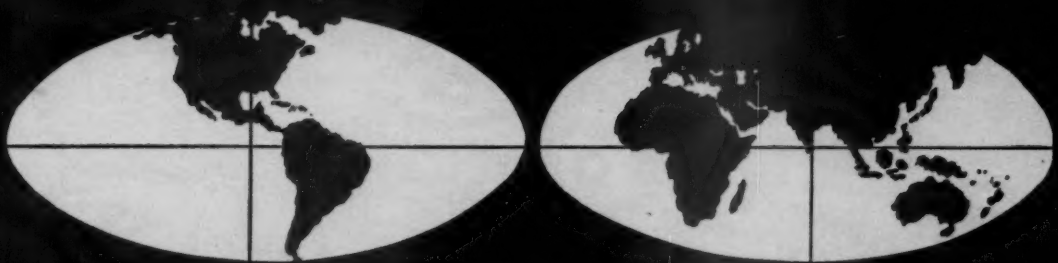

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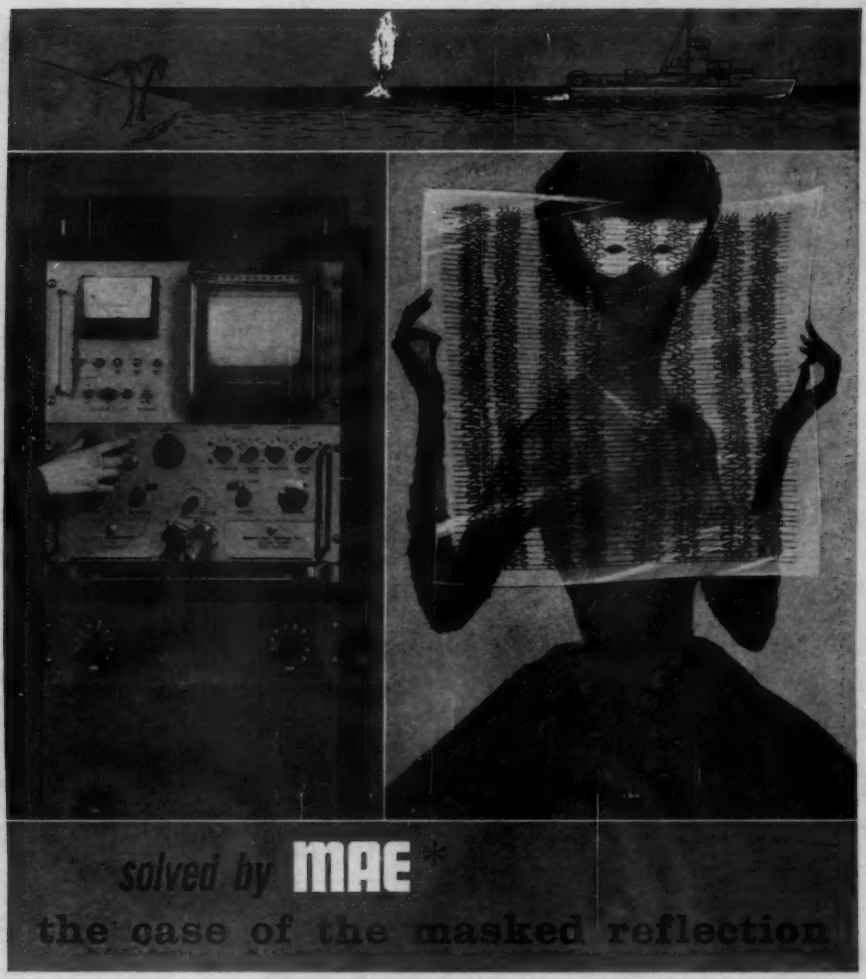

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